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EARTH ORBITAL TELEOPERATOR SYSTEMS EVALUATION
1978 YEAR END REPORT

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HUNTSVILLE FACILITY 3322 Memorial Parkway South, Huntsville, Alabama 35801

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EARTH ORBITAL TELEOPERATOR SYSTEMS EVALUATION

1978 YEAR END REPORT

Prepared For:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Prepared By:

Nicholas Shields, Jr.
Phillip H. Slaughter
Ronald G. Brye
David E. Henderson

ESSEX CORPORATION
Huntsville Facility
3322 South Memorial Parkway, Suite 8
Huntsville, Alabama 35801

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FOREWORD

The 1978 Teleoperator Systems Evaluations were centered around research activities in the Manipulator System Evaluation Laboratory and the Mobility System Evaluation Laboratory. This report documents the activities performed by the Essex technical staff including arrangement of test equipment, development of test procedures, conduct and results of tests performed, and facility additions and modifications.

The successful conclusion of this year's work would not have been possible without the involvement and dedication of Mr. Ed Guerin, the Contracting Officer's Representative, Mr. John Burch, Mr. Keith Clark, and Mr. Don Scott. Their participation in this program is gratefully acknowledged.

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ACRONYMS AND ABBREVIATIONS

A/D	Analog to Digital
CG	Center of Gravity
D/A	Digital to Analog
DOF	Degree of Freedom
DRM	Docking Retrieval Mechanism
ESAM	Extendible Stiff Arm Manipulator
FOV	Field of View
LOS	Line of Sight
LSI	Lear Seigler, Incorporated
LSS	Large Space Structures
MIT	Massachusetts Institute of Technology
MMC	Martin Marietta Corporation
MSI	Measurement Systems, Inc.
MU	Mobility Unit
NBS	National Bureau of Standards
PFMA	Protoflight Manipulator Arm
RMS	Remote Manipulator System
SEL	Systems Engineering Laboratories
SMM	Solar Maximum Mission
SRD	Satellite Retrieval Device
TD	Terminal Device
T/O	Teleoperator
Vdc	Volts, Direct Current

1.0 TELEOPERATOR TECHNOLOGY DEVELOPMENT

The mechanical extension of the human operator to remote and specialized environments poses a series of complex operational questions. What visual feedback is required by the human operator? What mechanical feedback is required by the operator? How much of a remotely managed operation should be automatically controlled and how much should be under human control? What are the effects of system parameters on the human operator's ability to carry out a series of remote tasks successfully? How can "a sense of presence" for the operator be introduced, or is one necessary in remotely operated tasks?

Essex has organized its technical and scientific team to investigate these questions through the conduct of specific laboratory and analytical studies. The intent of Essex' inquiries has not been to develop components for a teleoperator or to design a teleoperator system. Rather, it has been to determine the human operator requirements for remotely manned systems and to determine the particular effects that various system parameters have on human operator performance and, in so doing, to add to the Teleoperator Technology Development Program, certain design criteria based upon empirically derived data concerning the ultimate control system for a teleoperator, the human operator.

Essex has conducted its investigations in three major laboratories at NASA's George C. Marshall Space Flight Center (MSFC): the Visual System Evaluation Laboratory, the Manipulator System Evaluation Laboratory, and the Mobility System Evaluation Laboratory.

1.1 Visual System Evaluation Laboratory

The questions raised concerning visual scene requirements of the human operator for the effective control and conduct of remote tasks have been addressed in this laboratory. While much is known from the existing body of psychological knowledge concerning human visual perception, it was necessary to test the validity of this knowledge when the visual information was delivered via a video sensor and display system. Information included in the teleoperator technology data base concerning visual systems now includes:

- Sensor Systems
 - Multiple cameras
 - Vidicons
 - Silicon intensified detectors
 - Charged induction devices
 - Charged coupled devices
 - Monochromatic sensors
 - Color sensors
 - Low light level sensors
 - Fixed focal length

- Fixed field of view
- Dynamic zoom lens
- Monoptic sensors
- Stereoptic sensors

- Display Systems
 - Color displays
 - Monochromatic displays
 - Monoptic displays
 - Stereoptic displays
 - Split screen displays
 - Varying monitor sizes
 - Multiple displays
 - Augmented displays
 - Overlaid displays
 - Raster scan
 - Varying phosphors
 - Fresnel displays
 - Half field displays

- Transmission Parameters
 - Analog signals
 - Digitized signals
 - Narrow band pass filtered signals
 - Varying signal to noise ratios
 - Varying frame rate transmissions

- Environmental Parameters
 - Static scenes
 - Dynamic scenes
 - Two-dimensional scenes
 - Three-dimensional scenes
 - Camera configurations/geometries
 - Lighting configurations/geometries
 - Contrast conditions
 - Sensor pan, tilt and zoom

- Human Operator Performance Measures (using the above variables)
 - Visual acuity
 - Form recognition
 - Pattern recognition
 - Character recognition
 - Size estimation
 - Motion detection
 - Motion resolution
 - Distance estimation
 - Brightness discrimination
 - Alignment estimation
 - Color identification
 - Color discrimination
 - Estimation of vertical alignment.

1.2 MANIPULATOR SYSTEM EVALUATION LABORATORY

Utilizing video information as the primary feedback to the operator, we can now address questions concerning the effectiveness of operator performance using remote manipulator systems to perform operational type tasks. Current manipulator system investigations have produced information covering the following areas:

- Manipulator Arms
 - Bilateral
 - Single manipulator arm
 - General purpose arms
 - Specialized arms
 - Anthropomorphic arms
 - Non-anthropomorphic arms
 - Varying degrees-of-freedom arms
- End Effectors
 - General purpose dexterous effectors
 - Fixed purpose, specialized effectors
 - Prosthetic effectors
 - Specialized tool effectors
 - Non-anthropomorphic effectors
- Hand Controllers
 - Single joystick
 - Two-hand joystick
 - Rate controllers
 - Position controllers
 - Integrated, multi degrees-of-freedom controllers
 - Exoskeletal controllers
 - Toggle switch controllers
 - Replica controllers
- Control Schemes
 - Electromechanical link
 - Computer assisted
 - Computer resolved
 - Joint actuated
 - Tip position resolvers
- Manipulator Evaluation Criteria
 - Minimum position change
 - Tip position accuracy
 - Tip position stability
 - Position and orientation
 - Dynamic work envelope
 - Removal/replacement
 - Force/torque application
 - Manipulator dexterity
 - Specifically applied manipulator tasks.

1.3 MOBILITY SYSTEM EVALUATION LABORATORY

The Mobility System Evaluation Laboratory provides an environment in which to examine remote vehicle control, remote manipulator operations and televised feedback as an integrated system similar to those which will be incorporated on an operational teleoperator. At the present time, the most significant difference is that the mobility facility provides five degrees-of-freedom (DOF) for the test units rather than the six-degrees-of-freedom operational environment (z restricted).

Data generated from this facility were used to verify concepts derived from the manipulator laboratory and the visual system laboratory as well as to confirm special operational requirements such as rendezvous and docking, satellite capture and inspection. Details of simulations accomplished within this laboratory are given in Section 2.0 of this report.

1.4 OVERVIEW

The details of the laboratory and analytical studies are available in the documents included in the reference section of this report. These publications outline the research questions addressed, the approaches and methods taken to formulate valid answers to these questions and to present the findings of the experiments conducted. The references represent a very extensive body of information concerning the human operator in teleoperator systems and the effects of system parameters on the operator's capability to perform specified tasks. They contain the information which is essential to the appropriate design of a teleoperator system which has as its central strength, the unique processing, sensory, decision making, manipulative, and control abilities of the human operator.

1.5 FUTURE REQUIREMENTS

That some important steps have been taken to integrate the human operator more fully into remotely manned systems in not to say that all of the requirements have been satisfied or that all of the criteria have been identified. There is still a significant amount of information to be obtained.

The effects of conducting operations in the full six-degrees-of-freedom environment need to be determined. This, of course, implies that some additional capabilities be added to the existing simulation facility.

The incorporation of a fully functional manipulator system into the simulation facility's Mobility Unit (MU) would permit a detailed series of investigations concerning servicing, inspection and other delicate or dexterous tasks to be accomplished.

Remote operations can imply a sizable distance between controller and teleoperator in space applications. Because of this distance, some operational data need to be developed on the effects of time delay on human operator performance of remote tasks.



Utilizing the data base which presently exists, it is necessary to design and conduct a series of simulations which apply to actual proposed missions utilizing fairly high fidelity spacecraft mockups under realistic operational guidelines to validate teleoperator capabilities.

Using proposed system concepts, such as the Protoflight Manipulator Assembly (PFMA), it is also necessary to exercise the system under the Manipulator System Evaluation criteria developed by Essex to make a generalizable assessment of system performance.

In addition, there is a continuing requirement that advances in the state-of-the-art be investigated for possible teleoperator applications. For example, new computer systems for manipulator controller, image enhancement for visual scene feedback, new control and controller concepts, and other similar advances need to be identified and integrated into the Teleoperator Technology Development Program.

2.0 MOBILITY SYSTEM EVALUATION LABORATORY

This section describes the Mobility System Evaluation Laboratory, its components, and how this facility was used during 1978 to evaluate certain teleoperator guidance, control, and docking systems.

2.1 FACILITY DESCRIPTION

The evaluation facility is centered around a 111 m² black, epoxy, flat floor which is protected by a heavy, black fabric enclosure. The enclosure provides for the control of ambient light, dust, humidity, air flow, and similar variables which must be controlled during test and evaluation.

The flat floor provides a smooth surface on which air bearing vehicles can be floated. The principal vehicle is the Mobility Unit (MU) which simulates a teleoperator and is shown in Figure 2-1. The MU offers a motion base in up to five degrees of freedom (DOF) on which manipulators, grapplers, probes, camera configurations, and the like may be examined in an operational setting.

A detailed facility description including technical descriptions is included in Reference 3.

2.2 TEST EQUIPMENT

The free flying MU was designed to investigate the guidance, control, and docking problems associated with a small, unmanned, remotely controlled space vehicle in a near proximity rendezvous and docking situation. For this testing program, the MU had three DOF: two in translation (fore/aft and left/right) and one in attitude (yaw).

The crew command/control input devices were two (3 DOF each) spring-loaded, center-return, 7 cm (2.75 in) control sticks (Micro-Avionics, P/N MA-65-2AT) which functionally related to MU operation. Displacement of the left-hand controller corresponded to fore/aft and left/right movements of the MU. The third DOF was not connected. Displacement of the right-hand controller resulted in yaw movements. The other two DOFs (roll and pitch) were not used for these tests.

The operator performed all docking maneuvers using a commercial, 11-inch diagonal, black and white TV monitor located above and between the hand controllers (see Figure 2-2). The operator viewed either the TV display generated by the MU onboard camera(s) or the display generated by a camera mounted on the docking probe, depending on which experimental condition was being used. This docking probe, called the Docking Retrieval Mechanism (DRM), is discussed in Paragraph 2.6.

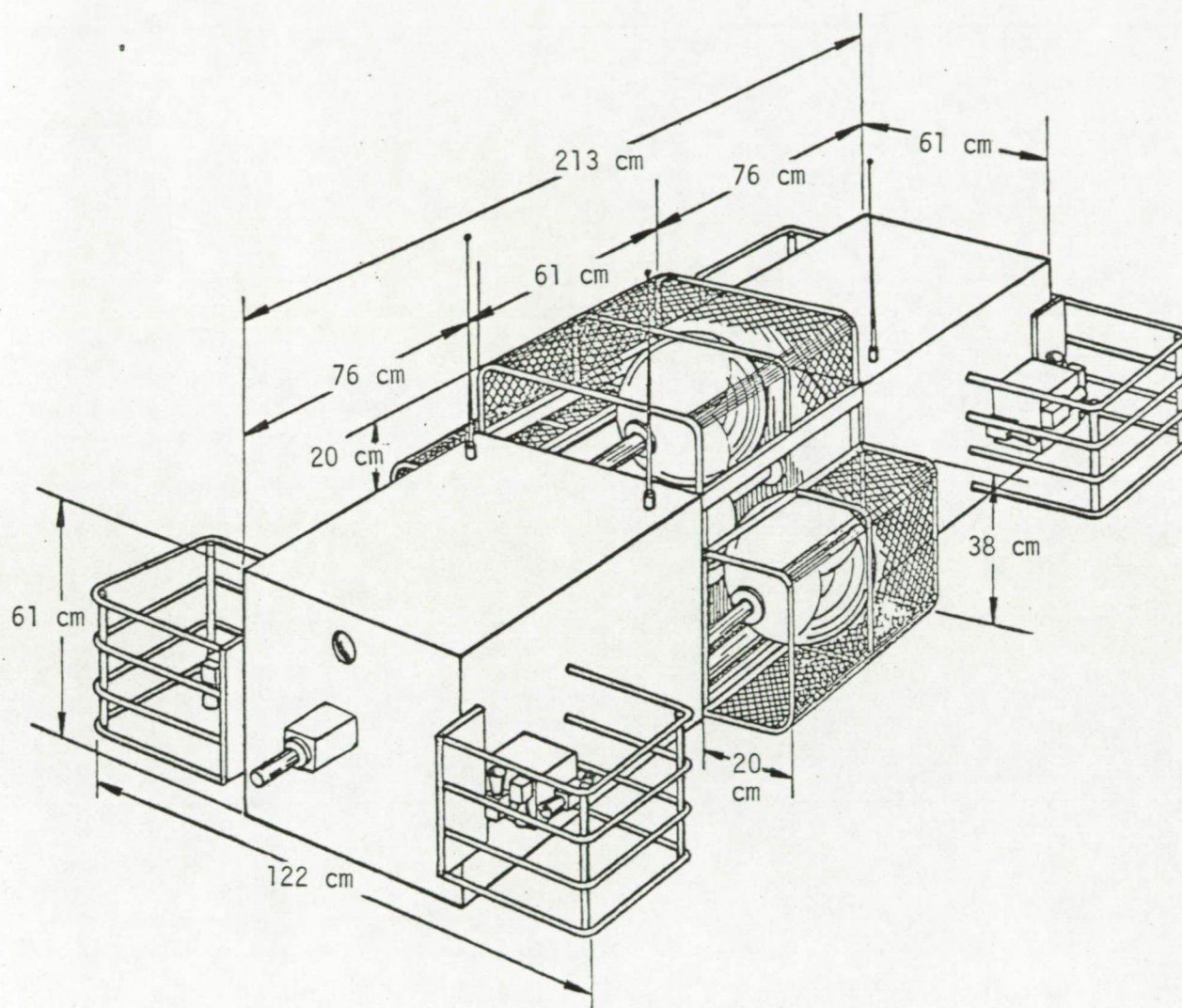


Figure 2-1: Mobility Unit Physical Dimensions

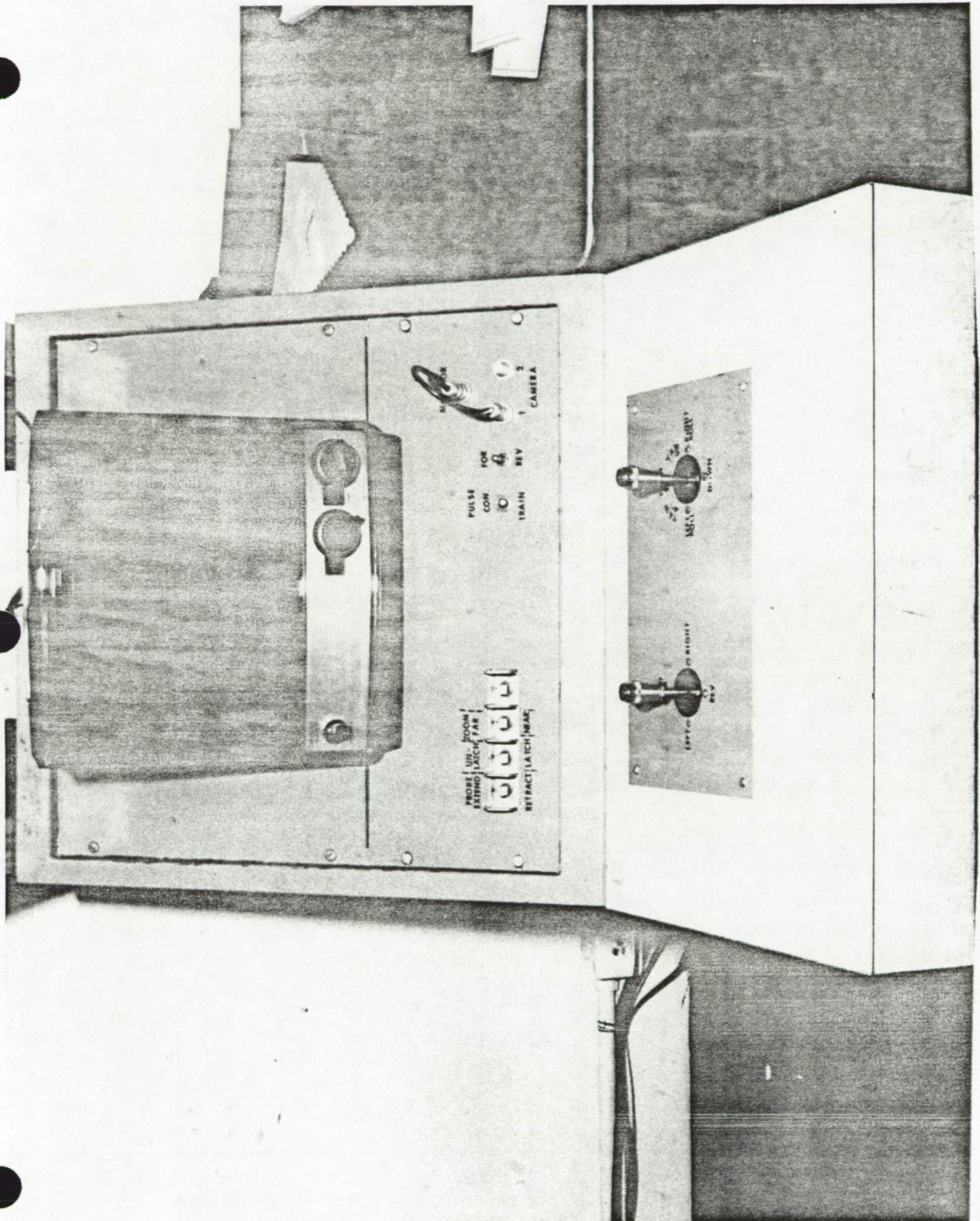


Figure 2-2: Operator's Station for Two-Hand Control Concept

The DRM control panel was employed when using the DRM to dock with the MU. The panel contained two three-position, spring-loaded toggle switches which activated the extend/retract or latch/unlatch drive mechanisms on the DRM. Complete technical information on the DRM is furnished in Reference 1, and the control panel is shown in Figure 2-2, above.

2.2.1 Command Subsystem

The command subsystem has nine subcarrier frequencies operating on nine 450 MHz range carrier frequencies which have the capability to be excited two at a time. This yields a potential of 36 command signals. The command signals are generated at the operator's console via the two hand controllers. The hand controller, when displaced, closes a set of relays which transmits binary signals to the MU. These signals activated appropriate solenoids to modify the MU position or attitude by thruster firings.

Thruster firing signals are of two types: (1) a constant mode in which the telemetered signal is transmitted for the duration of the command, resulting in a constant "ON"; and (2) a trained mode in which the telemetered signal is pulsed at approximately 5.5 bursts per second and is transmitted at this rate for the duration of the command.

2.2.2 Video Subsystem

The MU onboard camera was used for rendezvous and docking tests with the two-hand controller concept. This camera is mounted flush with the forward surface on the MU and boresighted with the longitudinal axis of the MU (see Figure 2-1, above).

The video subsystem is a Cohu Model 2840 camera which is a low light level model modified to operate on 28 Vdc. The camera lens is a Canon Model TV-16, 25 mm, 1:1.4 which uses an automatic iris control. Zoom and focus, however, were preset for the testing program.

2.2.3 Telemetry Subsystem

The telemetry subsystem operates in the 253 Mhz range and has the capability of 17 channels for data transceiving. Technical details on the telemetry subsystem are detailed in Reference 3.

2.2.4 Control Subsystem

The control subsystem tests described in this report operated in the open-loop or supervisory mode, where the operator determines the vehicle's orientation and velocity via video feedback and compensates by firing selected thrusters, namely fore/aft, left/right, and yaw. Technical details for the control subsystem have been described in Reference 3.

2.2.5 Propulsion Subsystem

The MU's propulsion system uses compressed air operated through four groups of four thrusters each that provide pure moment and axial thrust. The propulsion system is shown in Figure 2-3, and the thruster command logic is presented in Table 2-1.

Table 2-1: Thruster Command Logic

Thruster Command	Thruster Response
Foreward	14, 15
Aft	6, 7
Right	8, 16
Left	5, 13
Yaw Left	5, 16
Yaw Right	8, 13
Pitch Up	3, 4, 9, 10
Pitch Down	1, 2, 11, 12

The air bearing system consists of three 30.5 cm (12 in) circular pads, pressure regulated at $2.4 \times 10^5 \text{ N/m}^2$ (35 psi) to float the vehicle with a .05 mm (.002 in) clearance. The total volume of compressed air stored in the lower bay of the vehicle is $.074 \text{ m}^3$ (2.604 ft^3) at a pressure of $10.3 \times 10^6 \text{ N/m}^2$ (1500 psi).

The lower bay houses the compressed air supply, contains the air pads, and supports the upper bay. It also serves as a mounting support for the air bearing pedestal upon which the upper bay is mounted. This lower bay is 48.3 cm high and 116.8 cm in diameter (19 in x 46 in) and is painted a non-reflective flat black to minimize the operator's visual cues.

The propulsion system of the MU, as mentioned earlier, serves the dual purpose of vehicle translation and attitude control. Each group of four thrusters is clustered about the longitudinal axis of the vehicle (one group at each corner). Each thruster is controlled by a solenoid valve at the thrust chamber injector. Total volume of compressed air for the upper bay of the vehicle is 0.074 m^3 (2.6 ft^3) at a rated pressure of $10.3 \times 10^6 \text{ N/m}^2$ (1500 psi).

The unfueled mass of the MU is 572.4 kg (1262 lb) of which 419 kg (923 lb) is the top bay. Fueling the MU added 18.46 kg (40.7 lb) to the total mass. However, half of this was used for the air bearing pads leaving 9.2 kg for use by the propulsion system.

Fueling (pressurization) of the MU was modified this year by replacing

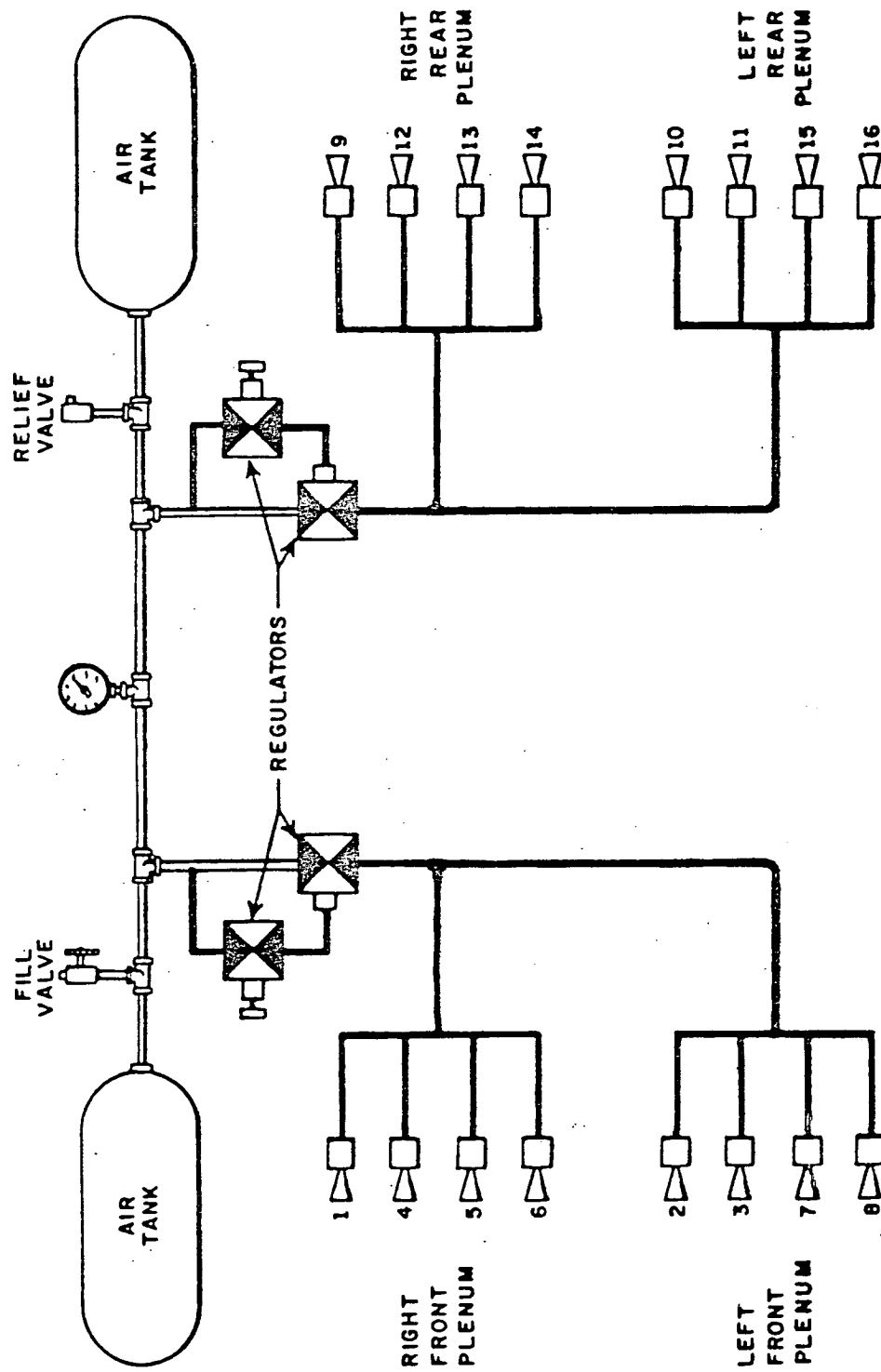


Figure 2-3: Compressed Air Propulsion System

the wall-mounted hand valves with switch-operated 28 Vdc solenoid valves, and the fittings on the MU with quick connect/disconnect couplers. These modifications provided test personnel with smoother and quicker response times between tests and ensured a more complete pressurization of the MU.

2.2.6 Docking Retrieval Mechanism

The Docking Retrieval Mechanism (DRM) is an extendible docking probe and was only used for part of the docking tests. The physical apparatus and the operating characteristics are presented in Paragraph 2.6.2 and Reference 3.

2.3 MAJOR RESEARCH QUESTIONS

During 1978, there were two primary questions concerning the design of the teleoperator guidance and control and docking systems that could be addressed by research conducted at the mobility laboratory. These research areas were:

1. Thruster Control Scheme - Several alternatives exist for transforming the input from the crew hand controller into thruster commands. The major thrust modes include constant thrust and a series of discrete thrusts. Data are needed to support selection of the control mode that minimizes fuel and power consumption, time to dock, and the number of aborts. Hand controller selection will also require specification of deadband and displacement forces and angles. The overriding question in the area was whether two hand controllers are required for translation and orientation or if one is adequate.

2. Solar Maximum Mission (SMM) Capture - Part of the T/O mission will be to capture and/or retrieve a payload class that will not have a dedicated capture mechanism. Therefore, the teleoperator will have to grapple with various protruding members such as an antenna, a jutting spar, etc., and perform some type of hard dock maneuver using minimal force and contact area. (A representative of this class of payload is the SMM spacecraft which has no dedicated docking device, is a large mass payload, and has a restricted grappling area.) The major research question in this area was whether a female capture device could dock with a short and small male appendage. Past efforts in this laboratory have always involved docking a male probe with a female drogue; therefore, new equipment and procedures were developed to test the inverse of this situation.

2.4 TESTS PERFORMED

Tests were conducted with the primary objective of gathering performance data on near-proximity maneuvering and final docking of a representative baseline configuration teleoperator with a target satellite. The secondary objective was to develop and refine the capability of the laboratory to

investigate proposed teleoperator guidance and control and docking systems and crew procedures related to final maneuvering and docking. As part of the refinement procedures related to the mobility laboratory, a number of engineering surveys were performed which are also described in this report.

The specific tests involved are:

- Evaluation of a two-hand controller concept as compared with a single hand controller concept, and
- Evaluation of two SMM camera/docking target combinations.

In both tests, the general procedure involved having the operator command and control the MU to close range over a known distance and a known range, from a known starting point to effect a dock. Data on elapsed time, fuel consumption, and aborted docking attempts were recorded. Also recorded were comments by the subjects about the test equipment and/or procedures for the particular test in progress.

2.5 ENGINEERING SURVEYS

A number of engineering surveys were conducted this year to document the MU baseline parameters and provide users of this facility with technical planning information. Another engineering survey was performed to determine if mass loading of the MU upper bay would affect operation of the center air bearing sphere. This is a preliminary step to building a full scale mockup of the TRS.

2.5.1 MU Pitch and Yaw Acceleration

This section describes the pitch and yaw acceleration values gathered using the MU with a constant thrust mode.

2.5.1.1 Objective

NASA requested that the pitch and yaw acceleration levels of the MU be defined for technical planning purposes.

2.5.1.2 Method

The MU was fully pressurized and temperature stabilized by a slow filling procedure and then balanced on the center air bearing sphere until just noticeable movement was detected.

The trials for yaw acceleration levels were conducted using a 360° rotation combined with a constant thrust mode. A total of five trials were performed with the dependent measure being elapsed time to complete a 360° rotation.

The trials for pitch acceleration levels were conducted in basically the

same manner, except that data were taken with the MU starting at a 0° (level) setting through a pitch down maneuver and terminating when it "bottomed-out" at 17.5°. Again, the primary dependent measure was elapsed time, and angular displacement was measured with a 180° level indicator, accurate to 0.5°.

Prior to conducting these tests, the MU thruster system was "exercised" by repeated thruster bursts which served the purpose of loosening the rubber diaphragms on the individual thrusters.

2.5.1.3 Results and Conclusions

The acceleration data were recorded as angular displacement acting through time with an initial velocity of zero and a mean terminal acceleration as shown below:

- Yaw
 - Elapsed Time ($\bar{X}$ of 5 trials) 15.7 seconds
 - Angular Displacement 360°
 - Number of Thrusters Firing 2

$$\bar{V} = 360/15.7 = 22.93^\circ/\text{S} = 0.40 \text{ radians/S} \quad (\text{Equation 1})$$

$$a = \frac{2\theta}{T^2} = 0.186^\circ/\text{S}^2 = 3.25 \times 10^{-3} \text{ radians/S}^2 \quad (\text{Equation 2}).$$

- Pitch
 - Elapsed Time ($\bar{X}$ of 5 trials) 4.35 seconds
 - Angular Displacement 17.5°
 - Number of Thrusters Firing 4

$$\bar{V} = 17.5/4.35 = 4.02^\circ/\text{S} = 0.070 \text{ radians/S} \quad (\text{Equation 3})$$

$$a = \frac{2\theta}{T^2} = 0.425^\circ/\text{S}^2 = 7.44 \times 10^{-3} \text{ radians/S}^2 \quad (\text{Equation 4})$$

where $\bar{V}$ is mean velocity,
a is acceleration.

The acceleration data in equations 2 and 4 are not firm enough to be used in developing figures of merit; the data from different trials may vary significantly over conditions such as balance of the MU on the center air bearing sphere, the condition of the rubber diaphragms on the thrusters, slight shifting of internal components within the MU, etc.

It was discovered that, prior to conducting any tests involving the electro-pneumatic thrusters, the thrusters should be exercised by repeated firings. For example, it was noted that firing each group of thrusters using a trained mode for 15-20 seconds will loosen the rubber diaphragms, thereby ensuring more reliable and valid man-machine data.

2.5.2 Thruster Impulse Survey

Technical data were gathered on the impulse force of the MU thruster system using a constant thrust mode.

2.5.2.1 Objective

NASA/MSFC requested that impulse data be provided on the MU thruster system under a forward movement using a constant thrust mode. The objective of the thruster impulse survey was to provide this data.

2.5.2.2 Method

This survey was conducted using two methodologies: (1) displacement in the position of the mobility unit with acceleration data measured over time to calculate impulse, and (2) "paper and pencil" calculations using data generated from a previous test series reported in Reference 3.

2.5.2.3 Results and Conclusions

An engineering survey of the MU forward acceleration level revealed the following data on impulse:

Distance	approximately 30 ft
Elapsed Time	28.9 seconds
Number of Thrusters Firing	2

$$a = \frac{2d}{T^2} = 0.0718 \text{ ft/s}^2 \quad (\text{Equation 5})$$

$$F = Ma = 2.90 \text{ ft-lbs (1.45 ft-lbs for each thruster)} \quad (\text{Equation 6})$$

$$= 12.90 \text{ N-S (6.45 N-S for each thruster).}$$

However, Reference 2 indicates the thrusters were bench calibrated at one ft-lb each, which indicates a 4.95 N-S impulse or a forward impulse of 9.8 N-S.

These data indicate that thruster impulse be defined within a range of 4.45 to 6.45 N-S for each thruster acting to displace the MU in the fore/aft or left/right directions. Each direction requires a minimum of two thruster firings; therefore, the total directional impulse is 8.9 to 12.9 N-S. Here again, as for the pitch and yaw acceleration values, the many interacting variables discourage a precise measure of the impulse.

2.5.3 Mobility Unit Fuel Consumption Survey

Technical data were gathered on the fuel consumption rates of the MU system as a function of three separate thrust modes--constant thrust, trained thrust, and, also for this fuel consumption survey, single pulse thrust.

2.5.3.1 Objective

The objective of the survey was to define fuel consumption rates for the MU for the thrust modes. These were to be expressed in engineering equivalencies suitable for technical planning purposes.

2.5.3.2 Method

To calculate fuel consumption rates, the basic procedure was to evaluate differential pressure acting over time and then convert and express these data in mass flow rates for the three thrust modes. To do so, the following variables for fuel consumption were defined:

Rated Tank Volume at Rated Pressure	7.52 m ³ @ 10.3 x 10 ⁶ N/m ² (265.7 ft ³ @ 1500 psig)
Dry Air Mass	1.227 kg/m ³ (0.07657 lb/ft ³)
therefore, at rated pressure = 20.35 lb mass	
Number of Thrusters Firing	2.

The methods used in evaluating fuel consumption for each thrust mode are described below.

Constant Thrust - The procedure was to fire the thrusters for a known length of time and record the drop in pressure from the onboard pressure gauge.

Trained Pulse Thrust - The procedure was similar to the method for constant thrust with two exceptions: (1) the trained pulse was verified by operation to be approximately 5.5 pulses/second; and (2) the thruster firing times were longer. Again, the dependent measure was drop in pressure as recorded directly from the onboard pressure gauge.

Single Pulse Thrust - The single pulse thrust mode did not lend itself easily to calculating thrust over time since it is basically a single pulse over a fixed time (a mean pulse of 0.33 seconds). Therefore, these data were collected by two different methods: (1) 100 pulses and record differential pressure; and (2) number of pulses to affect a 50 psi drop over a total of 200 psi.

Fuel consumption was recorded as the differential between starting and ending pressure. These data were then expressed as (1) percent of fuel consumed with respect to a 10.3 x 10⁶ N/m² (1500 psi) starting pressure, and (2) fuel (i.e., compressed air) mass used.

Percent of fuel used was expressed by the following formula:

$$\% \text{ of fuel} = \frac{P_{\text{start}} - P_{\text{end}}}{P_{\text{start}}} \times 100$$

where P_{end} is ending pressure for each trial,

P_{start} is starting pressure for each trial ($10.3 \times 10^6 \text{ N/m}^2$
or 1500 psi).

The mass of the compressed air used for propulsion during a run was determined by the following equation:

$$M = pV(\Delta P)$$

where M is mass of air used (kg),

p is density of air at 1 atmosphere pressure (1.227 kg/m^3)

V is volume of air tanks ($.07375 \text{ m}^3$).

ΔP is the pressure drop in atmospheres (atm) and is expressed by the following equation:

$$\Delta P_{\text{atm}} = \frac{P_{\text{start}} - P_{\text{end}}}{P_{1 \text{ atm}}}$$

Substituting,

$$M = (1.227 \frac{\text{kg}}{\text{m}^3}) (.07375 \text{ m}^3) \left(\frac{P_{\text{start}} - P_{\text{end}}}{P_{1 \text{ atm}}} \right)$$

$$M = .0905 \text{ kg} \left(\frac{P_{\text{start}} - P_{\text{end}}}{P_{1 \text{ atm}}} \right). \quad (\text{Equation 7})$$

where $P_{1 \text{ atm}}$ is the pressure of one atmosphere expressed in the same units as P_{start} and P_{end} (i.e., kg/m^2).

2.5.3.3 Results and Conclusions

The fuel consumption data for the three thrust modes are presented in Table 2-2. This information is summarized in Table 2-3. These data, as with the data from the surveys discussed earlier in this document, do not reflect absolute values due to the many interacting variables. Rather, they are provided here as indicators for use in general planning.

Table 2-2: Fuel Consumption Data

THRUST MODE	THRUSTER FIRING TIME (SEC.)	STARTING PRESSURE (PSI)	ENDING PRESSURE (PSI)	ΔPSI
<u>Constant:</u>				
Trial #1	10	1450	1300	150
	20	1300	1200	100
	30	1200	1050	150
	40	1050	925	125
Trial #2	20	1550	1250	300
	40	1250	975	275
Trial #3	40	1550	950	600
<u>Trained:</u>				
Trial #1	20	1300	1050	250
	40	1050	825	225
	60	825	600	225
	80	600	400	200
Trial #2	40	1540	1025	515
	80	1025	625	400
Trial #3	80	1525	600	925
<u>Single Pulse:</u>				
Trial #1		1400	1175	225
(Completed 100 pulses)				
Trial #2		1175	1125	50
Trial #3		1125	1075	50
Trial #4		1075	1025	50
Trial #5		1025	975	50

(Recorded number of pulses to affect a Δ50 psi)

Table 2-3: Fuel Consumption Summary

Thruster Mode	Mean Fuel Consumption Rate (ΔP)	Mean Flow Rate (Mass/Second)
Constant	$9.58 \times 10^3 \text{ N/m}^2/\text{S}$ (13.9 psi/S)	0.086 kg/S (0.189 lb m/S)
Trained Pulse	$79.3 \times 10^3 \text{ N/m}^2/\text{S}$ (11.5 psi/S)	0.0706 kg/S (0.156 lb m/S)
Single Pulse	$14.82 \times 10^3 \text{ N/m}^2/\text{cs}^*$ (2.15 psi/cs*)	0.0133 kg/cs* (.02924 lb m/cs*)

*cs = command signal

One such application is the determination of what percentage of the total elapsed time for rendezvous and docking for a particular test condition is represented by command time (which is the amount of time the thrusters were firing and fuel was being consumed).

Command time is calculated from the following general equation:

$$\text{Command Time} = \frac{(\%_{FC}) (P_{\text{Start}})}{K} \quad (\text{Equation 8})$$

where $\%_{FC}$ is the percentage onboard,

P_{Start} is 1500 psi,

K is fuel consumption value for the particular thrust mode employed; i.e.,

Constant = 13.9 psi/S

Trained = 11.5 psi/S

Single Pulse = 6.45 psi/S.

This equation will give the amount of time the thrusters were fired for a particular test condition. The percentage of command time to total time can then be calculated by dividing the command time by the total elapsed time.

In calculating any such percentage figures, however, it must be understood that no set values may be established based on present findings. Only the broadest general indicators of relative difficulty are possible, since the percentages will vary not only as a function of the command mode employed but also among specific trials written within each command mode.

While not absolute values, the different percentages of total time consumed by commanding the MU in any of the three command modes and over various trials may be helpful in establishing a relative index of rendezvous and docking difficulty. In general, the greater the command time with respect to total elapsed time, the more difficult the particular test condition being exercised.

Determination of command time percentages, however, do not show what portions of that time were used for translation commands and attitude commands. Distinguishing between the influence of translation and attitude commands is one of the problems that remains to be resolved.

2.5.4 Mass Loading of the Mobility Unit Upper Bay

Nominal operation of the upper bay was measured, with respect to mass loading of the center air bearing sphere.

2.5.4.1 Objective

The two primary objectives of this engineering survey were: (1) to determine whether the center air bearing sphere would support the upper bay of the MU with an added load of 143 kg (316 lbs), and (2) to determine whether the MU upper bay could be balanced with this additional load.

2.5.4.2 Method

The MU upper bay was balanced as closely as possible with the center air bearing sphere set at $2.76 \times 10^5 \text{ N/m}^2$ (40 psi). A forklift was then used to support the upper bay while the additional load was placed on top of the MU. When the MU load reached the designated weight, the air bearing pressure was recorded and the MU rechecked for balance.

2.5.4.3 Results and Conclusions

The pressure recorded for the center air bearing was $3.79 \times 10^5 \text{ N/m}^2$ (55 psi), which still allowed maintenance of a frictionless surface. Concerning the first objective, therefore, it was determined that the center air bearing can tolerate the extra load and perform as intended.

With regard to the second objective, it was determined by consensus of the test personnel that the MU upper bay can be balanced even though loaded with the additional 143 kg of mass.

2.5.5 Epoxy Sampling Survey

Epoxy was received which will be used to resurface the flat floor at the mobility laboratory. Twenty-four samples were cured from this epoxy and were surveyed to determine if it will satisfy the requirements of this laboratory.

2.5.5.1 Objective

NASA requested that the sampling study be performed on the new epoxy purchased to resurface the mobility laboratory floor. The sampling procedure was performed to verify that the epoxy, when cured, would meet the requirements of a bubble-free, evenly cured, smooth surface, with a uniform black color.

2.5.5.2 Method

The epoxy, type 109B71, manufactured by the Moran Corporation, is identical to that already used on the existing flat floor surface. It was delivered to NASA/MSFC in two ready-to-mix batches of resin and hardener. The resin (Part A) was delivered in six 0.114 m³ (30 gallon) barrels, and the hardener (Part B) was delivered in 24 0.019 m³ (5 gallon) containers. The mixing ratio was 1.5 parts resin to 1 part hardener.

A total of 24 individual samples were prepared for this study. Each sample contained 304 grams of resin mixed with 195 grams of hardener (see Table 2-4).

Prior to the pulling of the resin samples from each barrel, the contents were thoroughly mixed for a minimum of three minutes and then visually inspected for an even mixture. The resin samples were individually pulled and poured into a container. The hardener samples were then individually pulled, mixed with a resin sample, and repoured into a separate 18.41 by 1.27 cm (7.25 by 0.5 in) clean mixing bowl. The samples were then placed next to the flat floor, which is within an enclosed area and is maintained at a relatively constant temperature (73°F), and were allowed to cure for three days. During the initial curing period, the samples' temperatures were recorded every half hour over a 2-1/2 hour period. After three days, the samples were inspected to verify that they all met the requirements specified in the objective.

2.5.5.3 Results and Conclusions

Twenty-four samples of the epoxy were evaluated with the following results:

- Smooth, bubble-free with an even surface texture
- Identical and evenly distributed black color
- Six samples cut in half exhibiting an even, hard mix throughout.

It appears from the above that the new epoxy will meet the requirements needed to resurface the existing flat floor of the mobility laboratory. When the resurfacing is completed, the flat floor will be measured for surface uniformity. If this is achieved, it will maintain the validity of future test findings.

Table 2-4: Mix Table for Resin and Hardener Samples

		Hardener Container Label (195 gm)																							
		A				B				C				D				E				F			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Resin Container Label (304 gm)	A	Mix 1																							
	B	Mix 2																							
	C	Mix 3																							
	D	Mix 4																							
	E	Mix 5																							
	F	Mix 6																							

2.5.6 Engineering Survey Summary

Part of the overall research program was to define the operational characteristics of the existing simulation hardware and identify desirable system modifications. A portion of this effort was directed towards enlarging the capabilities of the mobility laboratory by improving both the hardware and software capabilities.

The engineering survey conducted revealed the following general conclusions:

- Yaw and pitch acceleration values of the MU are $0.19^\circ/\text{sec}^2$ and $0.43^\circ/\text{sec}^2$, respectively
- MU thruster impulse ranges between 4.5 to 6.5 N-S for each thruster, with a mean value of 5.5 N-S
- MU mean fuel consumption rates under conditions of constant thrust, trained pulse thrust, and a single pulse thrust are $95.8 \times 10^3 \text{ N/m}^2/\text{S}$, $79.3 \times 10^3 \text{ N/m}^2/\text{S}$, and $14.8 \times 10^3 \text{ N/m}^2/\text{command signal}$
- The MU propulsion system's mean air mass flow rate under conditions of constant thrust, trained pulse thrust, and single pulse thrust are 0.086 kg/S, 0.071 kg/S, and 0.010 kg/command signal

- Fuel consumption (air pressure drop) and mass flow rate values appear to be relatively linear over time and pressure
- The MU, as presently configured, will hold an additional 143 kg of weight and still maintain balance in 5 DOF. This satisfies requirements for testing a full scale teleoperator mockup
- The new epoxy will meet the requirements for resurfacing the flat floor.

2.6 EVALUATION OF A TWO-HAND CONTROLLER CONCEPT

During the year, evaluations were conducted to determine the advantages of a two-hand controller concept in performing rendezvous and docking maneuvers (1) using the MU, and (2) using the DRM. The information gathered was compared with previously collected data using a single right hand integrated controller.

The two-hand controller was evaluated using the MU to rendezvous and dock with a target simulating a small mass satellite (equal to a mass smaller than that of the MU), and with a large mass satellite (more mass than the MU). A detailed description of this evaluation is presented in Section 2.6.1 of this report. The evaluation was conducted under the constant thrust and trained pulse thrust modes.

Next, data concerning operation of the two hand controller using the DRM to capture and retrieve a satellite were collected. This was also performed using both the constant and the trained pulse thrust modes. The description of this evaluation is presented in Section 2.6.2 of this report.

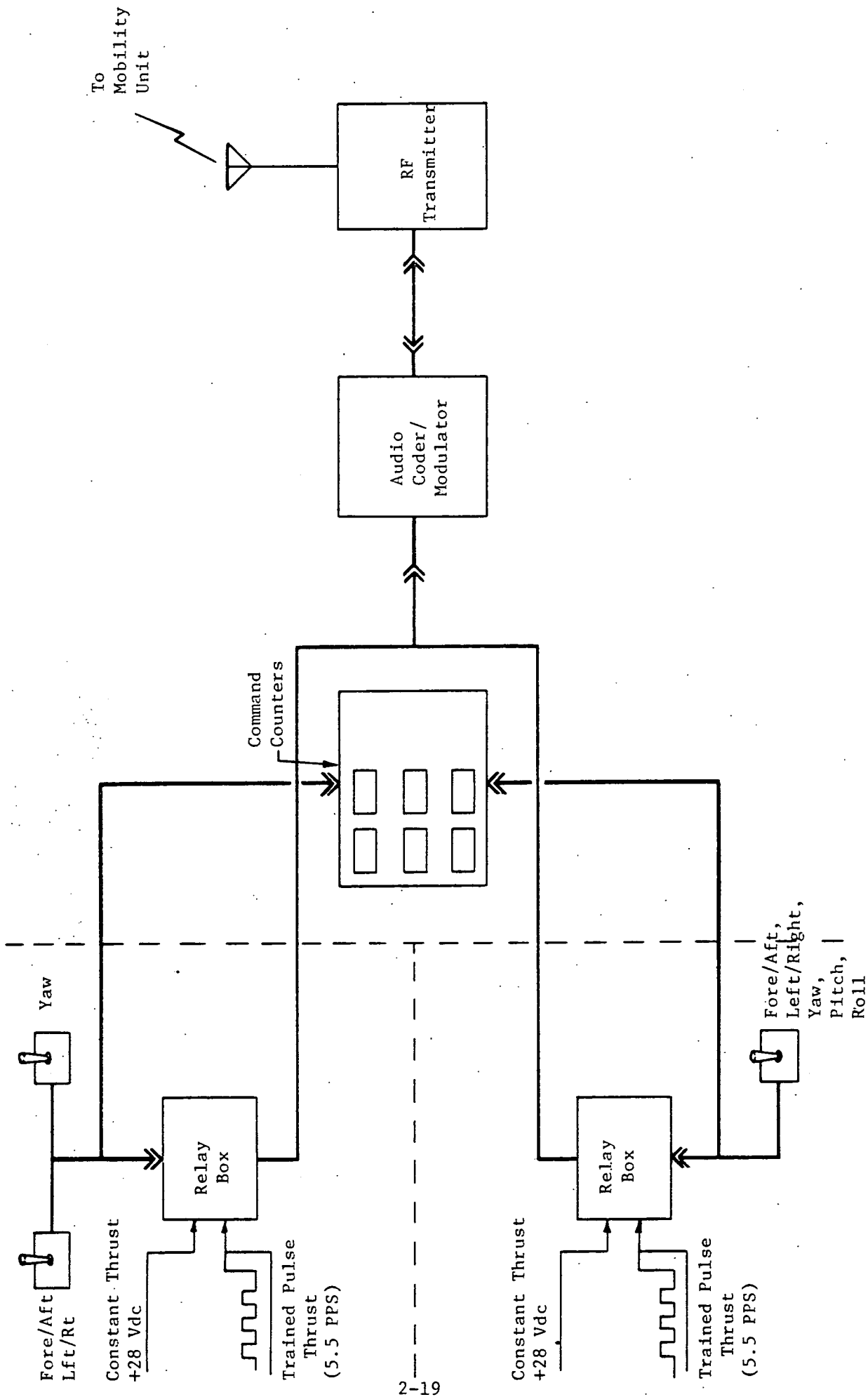
Information collected on the use of the two-hand controller for the MU and the DRM docking evaluations was compared with data collected during the previous year's work pertaining to the same operations using the one-hand controller. The outcome of this comparison is included in Paragraphs 2.6.1.5 and 2.6.2.5 below.

The control station was modified for the evaluations of the two-hand controller by installing a separate control panel with two spring-loaded, center-return 3 DOF displacement hand controllers. The controllers, when displaced, functionally corresponded to the commanded direction of the MU. Displacement of the left hand controller resulted in fore/aft and left/right movements. Displacement of the right hand controller resulted in pitch, roll and yaw movements. (See Figure 2-2, above.)

A black and white 11-in TV monitor (Sony Corporation, Model CVM-115, 525 line scan) was mounted directly in front of the subject and provided a view from the onboard camera via channel 9 VHF (186-192 MHz).

The control block diagram is functionally shown in Figure 2-4. Included

Two-Hand Controller



One-Hand Controller

Figure 2-4: Two-Hand and One-Hand RF Control Link

in this figure is the single 5 DOF hand controller for comparison. As indicated in the figure, the basic change made was separating the control functions into left hand (translation) and right hand (attitude) commands. This bilateral command concept is consistent with previous NASA controller concepts.

2.6.1 Rendezvous and Docking Maneuvers Using the Mobility Unit

2.6.1.1 Purpose

The purpose of this evaluation was (1) to collect data on the operation of a two-hand controller concept using the MU to rendezvous and dock with a target, and (2) to compare these data with information already collected on the single-hand controller used in a previous satellite docking task employing the MU.

2.6.1.2 Apparatus and Methodology

Figure 2-5 shows the basic elements of the test system.

The target payload used for docking is depicted in Figure 2-6 and shown as it is approached by the MU in Figure 2-7. The overall dimensions are identical to the MU. The roll and pitch axes were locked for the test duration; the satellite, however, was used in a passive 3 DOF mode (yaw, left-right, and fore/aft) for half the tests in order to simulate a low mass-class payload condition.

The test method employed for this test dictated that half of the trials be conducted with the target satellite in a fixed position on the air bearing floor to simulate a large mass target. The other half was conducted with the target free floating in position (fore/aft and left/right) and attitude (yaw) to simulate a small mass class satellite that would be disturbed by thruster impingement.

The general procedure for each trial consisted of the operator commanding the MU to approach the target which was located in the center of the floor. The operator made continual alignments of the MU position and attitude to fly the probe into the drogue. When a hard dock was successful, a docking latch lamp illuminated on the operator's panel. If a docking was aborted, as indicated by backing away and increasing the range, a docking trajectory was re-established and another docking attempt was made. At the completion of each docking trial, the dependent data were recorded, the MU was repositioned, and a new trial was begun.

2.6.1.3 Experimental Design

The independent variables were:

- Target satellite mass class
 - Large (stable, attitude locked, no air bearing pads)
 - Small (passive, attitude locked, using air bearing pads)

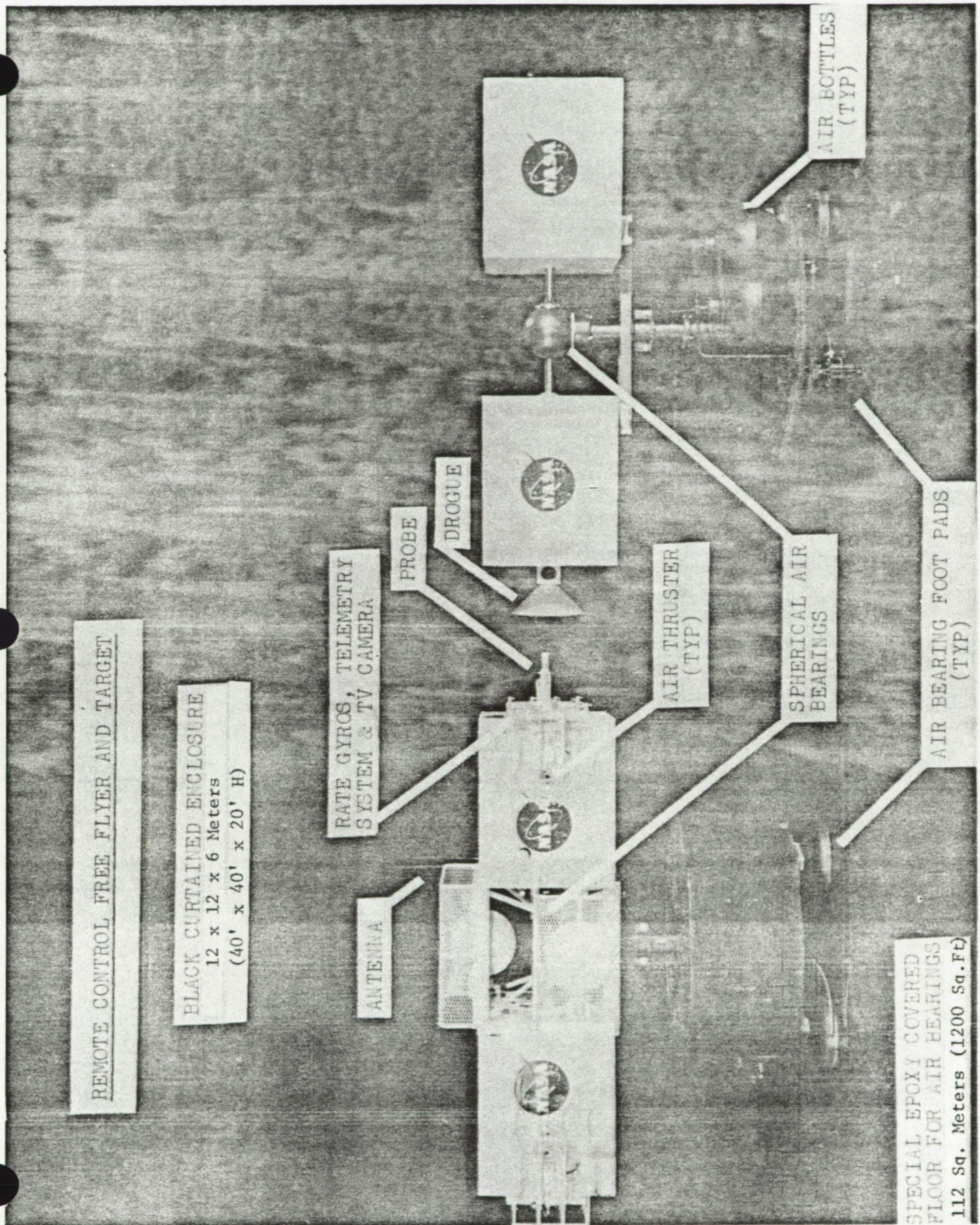


Figure 2-5: Mobility Unit and Payload Target

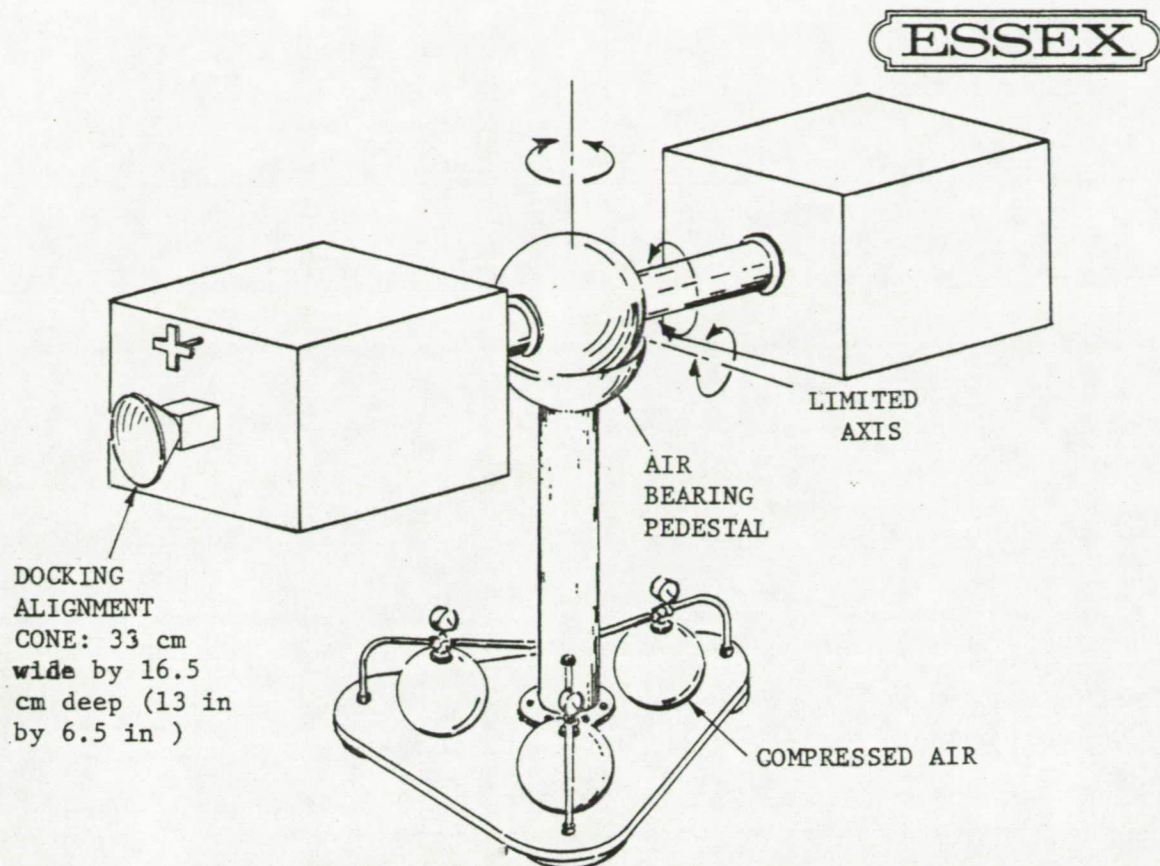


Figure 2-6: Docking Satellite Configuration

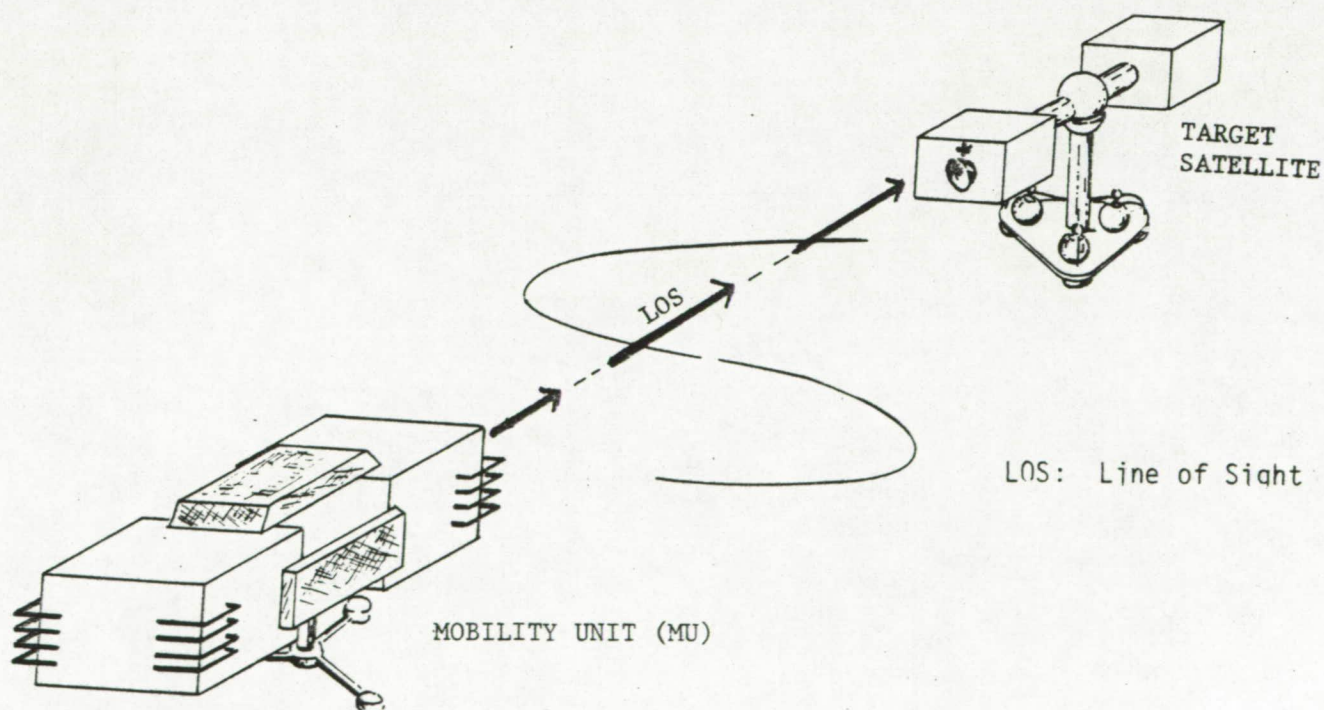


Figure 2-7: Docking Simulation Concept

- MU thrust mode
 - Constant (thrusters fired when controller was displaced from center position)
 - Trained pulse (thrusters fired at approximately 5.5 pulses/second when controller was displaced from center position).

The control variables were:

- Test area lighting - two banks of two 1250 watt quartz iodide lamps
- Initial propellant pressure - $10.3 \times 10^6 \text{ N/m}^2$ (1500 psi)
- MU/target initial position - boresighted
- Battery voltage - 28 Vdc
- Initial range (MU CG to satellite CG) - approximately 7.6 m (25 ft)
- Operator's TV monitor - daily check for high quality picture
- Initial position of target satellite - approximate center of floor
- Test surface - daily cleaning
- Subjects - four experienced subjects.

The dependent measures recorded during each test were:

- Elapsed time for docking
- Fuel consumed for docking
- Number of aborts.

Elapsed Time for Docking - The time required for docking is an obvious figure of merit for system/operator performance. Presumably the longer the time required, the greater the difficulty of the tasks associated with a particular test condition. In addition, studying completion time as a function of the independent variables employed permits detection of differential effects of these variables on different tasks. For example, attitude control system effects would be expected during the final approach to a greater degree than during initial translation. Furthermore, completion time data will be required for mission timeline planning and workload analysis. If task completion were time constrained during a mission, such data could be used to analyze the probability of task completion in connection with reliability analyses.

Fuel Consumed for Docking - The considerations which were stated in connection with completion time also apply to fuel consumption. This measure serves as a performance figure of merit, particularly since errors in aligning the MU and satellite body axes will require correction which will be reflected in increased fuel expenditure. Data on distributions of fuel required will also be useful in determining system design requirements.

Number of Aborts - The number of test aborts was recorded, and this information was stored for possible future use.

2.6.1.4 Results and Conclusions

The two-hand controller evaluation using the MU involved four experienced test subjects completing rendezvous and docking maneuvers under two thrust

modes and two target mass conditions. The mean data are summarized and presented for elapsed time (Figure 2-8) and for fuel consumption (Figure 2-9).

The mean elapsed time for the two-hand controller concept was 168.3 seconds compared to 193.2 seconds for the single-hand controller. However, the data indicate the greatest reduction in elapsed time for the two-hand controller is realized under conditions of a floating target and a constant thrust mode.

The mean fuel mass consumption for the two-hand controller over all conditions was 187.7 Kg (414.1 psi) compared with 177.8 Kg (392.2 psi) for the single-hand controller.

2.6.2 Rendezvous and Docking Maneuvers Using The DRM

2.6.2.1 Purpose

The two main objectives of this evaluation were: (1) to collect data on the operation of a two-hand controller concept using the DRM to rendezvous and dock with a target satellite, and (2) to compare these data with the results from the previous year's work on these same operations using the single hand controller.

2.6.2.2 Apparatus and Methodology

The primary test apparatus used for this test was the Martin Marietta DRM engineering prototype model which was designed and fabricated for MSFC for evaluation in the mobility laboratory. Reference 1 provides a complete technical description of the DRM, and Figure 2-10 shows the DRM in position to capture a payload.

The DRM was located just at the outside edge of the air bearing surface (as shown in Figure 2-11), and was mounted on a heavy-duty, adjustable height stand.

The DRM control panel was hardwired into the operator's control panel (as shown in Figure 2-2, above). It contained a pair of two-position spring-loaded toggle switches which were activated by the operator's left hand. These switches controlled the extend/retract and latch/unlatch functions of the DRM. Because the DRM switches were closely grouped and many times the subjects "felt" for the switches during a test, guard rails were installed to increase the likelihood of their actuating the correct switch.

The payload target used for this test was the MU configured with the DRM docking ring on the aft end (Figure 2-12). This configuration dictated that the MU would respond directly opposite to the command signal generated from the controllers (the operator viewed the MU from a probe-mounted camera). Consequently, a separate command circuit was installed at the control station which reversed the RF command signals transmitted to the MU. For example, when a forward thrust command was given to the teleoperator, the MU received an aft command signal. This signal reversal was consistent for all three degrees of freedom.

2 HC = Two-Hand Controller
 1 HC = Single-Hand Controller

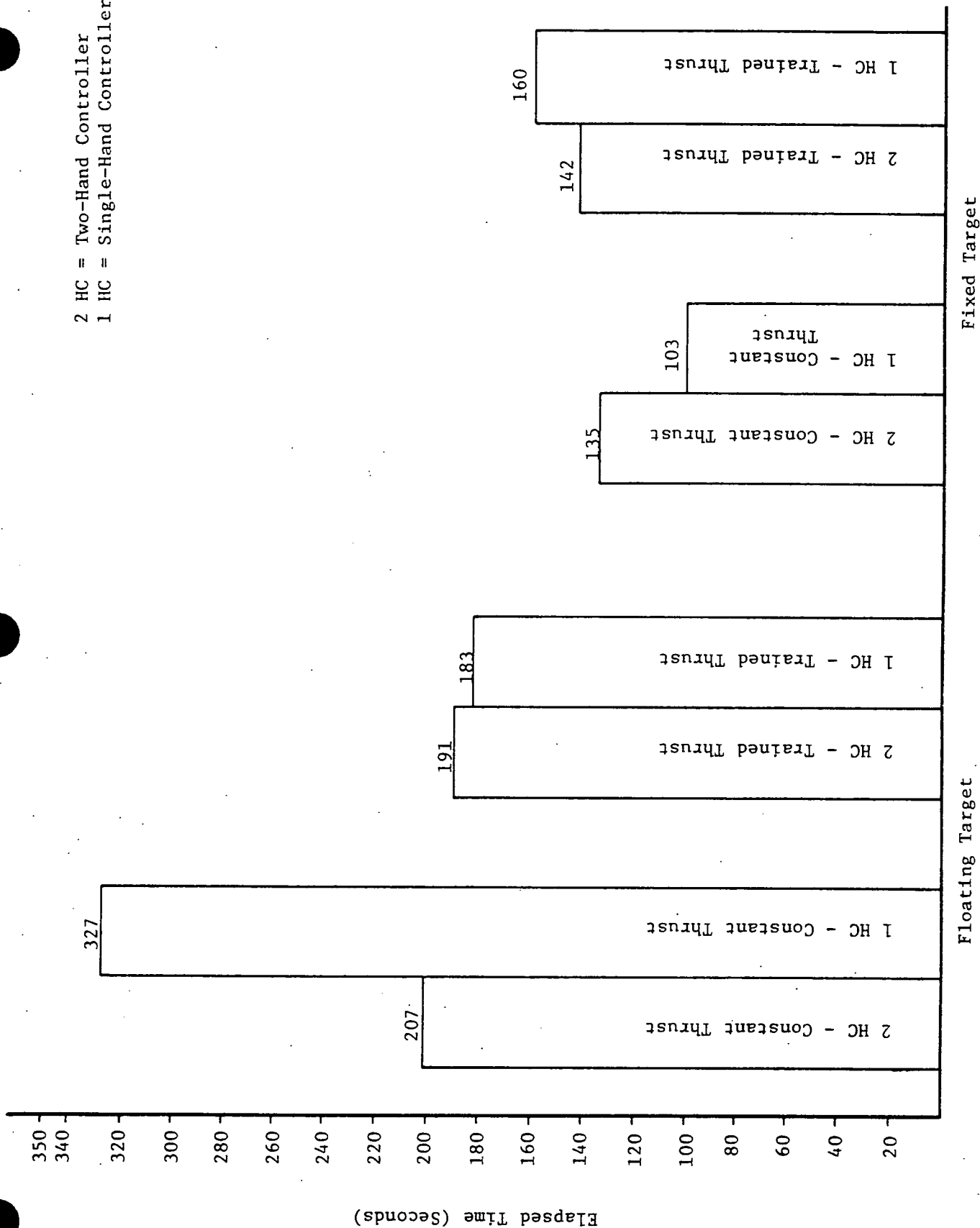


Figure 2-8: Mean Elapsed Time for Two-Hand vs One-Hand Controller Using the Mobility Unit

2 HC = Two-Hand Controller
 1 HC = Single-Hand Controller

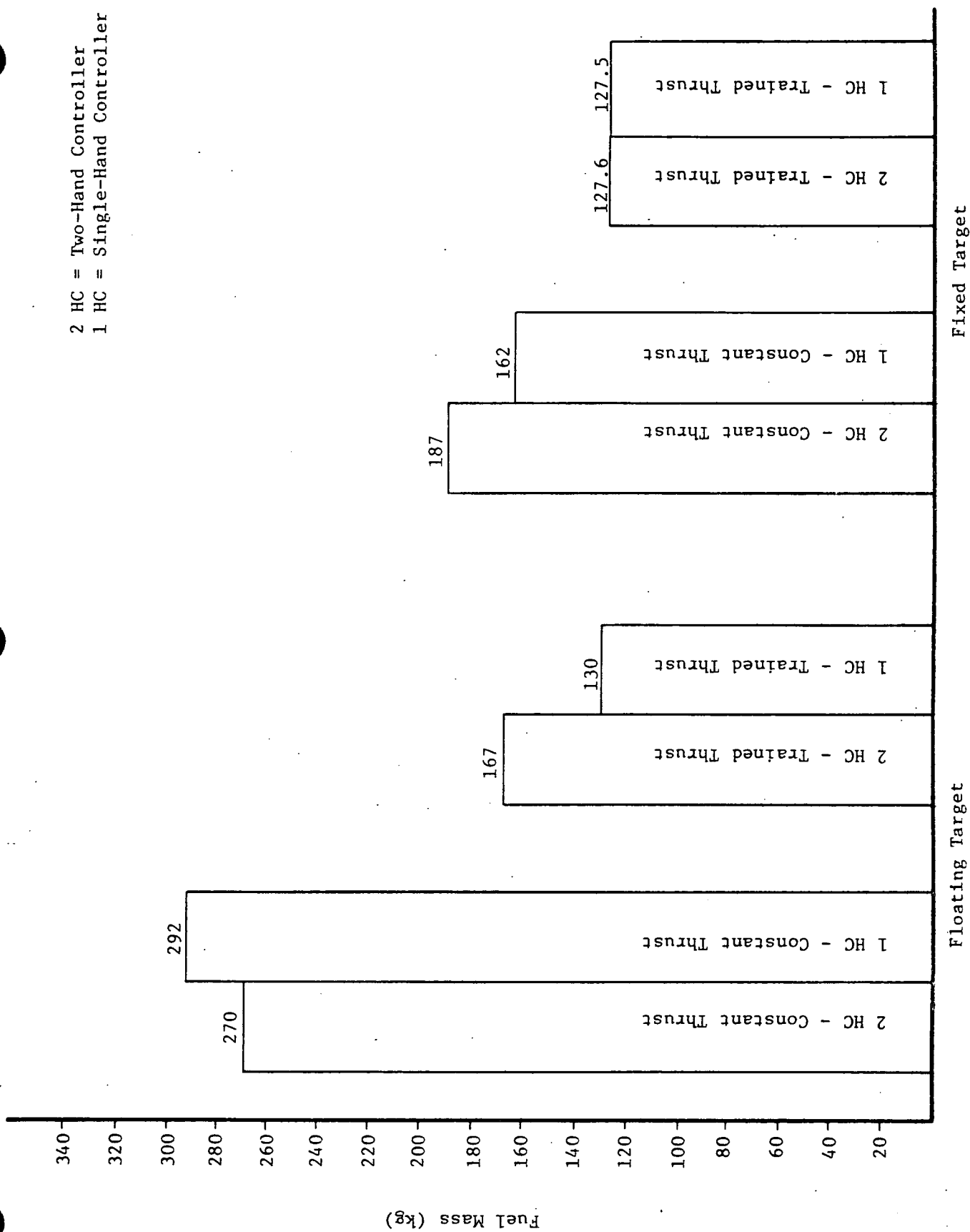


Figure 2-9: Mean Fuel Consumption for Two-Hand vs One-Hand Controller Using the Mobility Unit

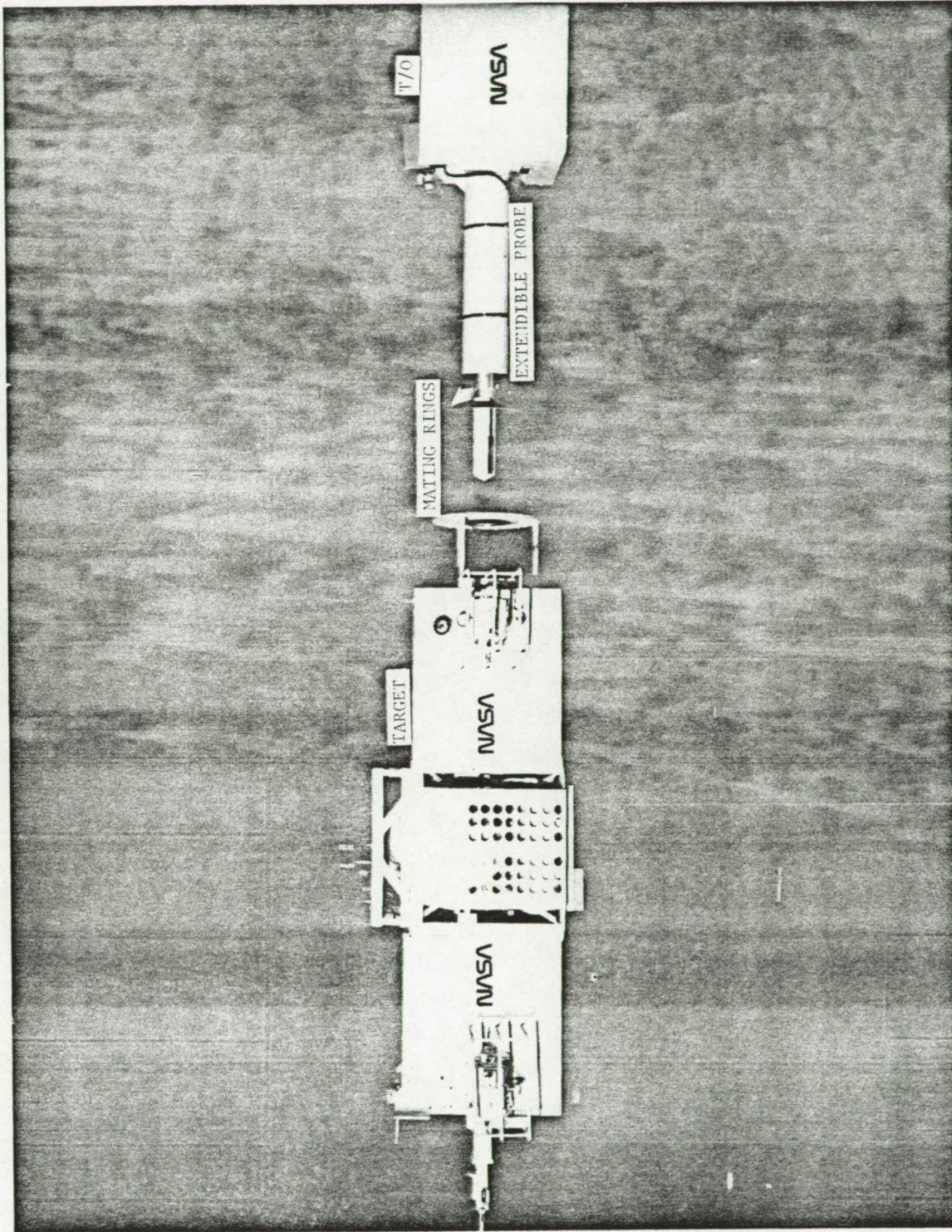


Figure 2-10: DRM in Position to Capture Payload Target

2-28

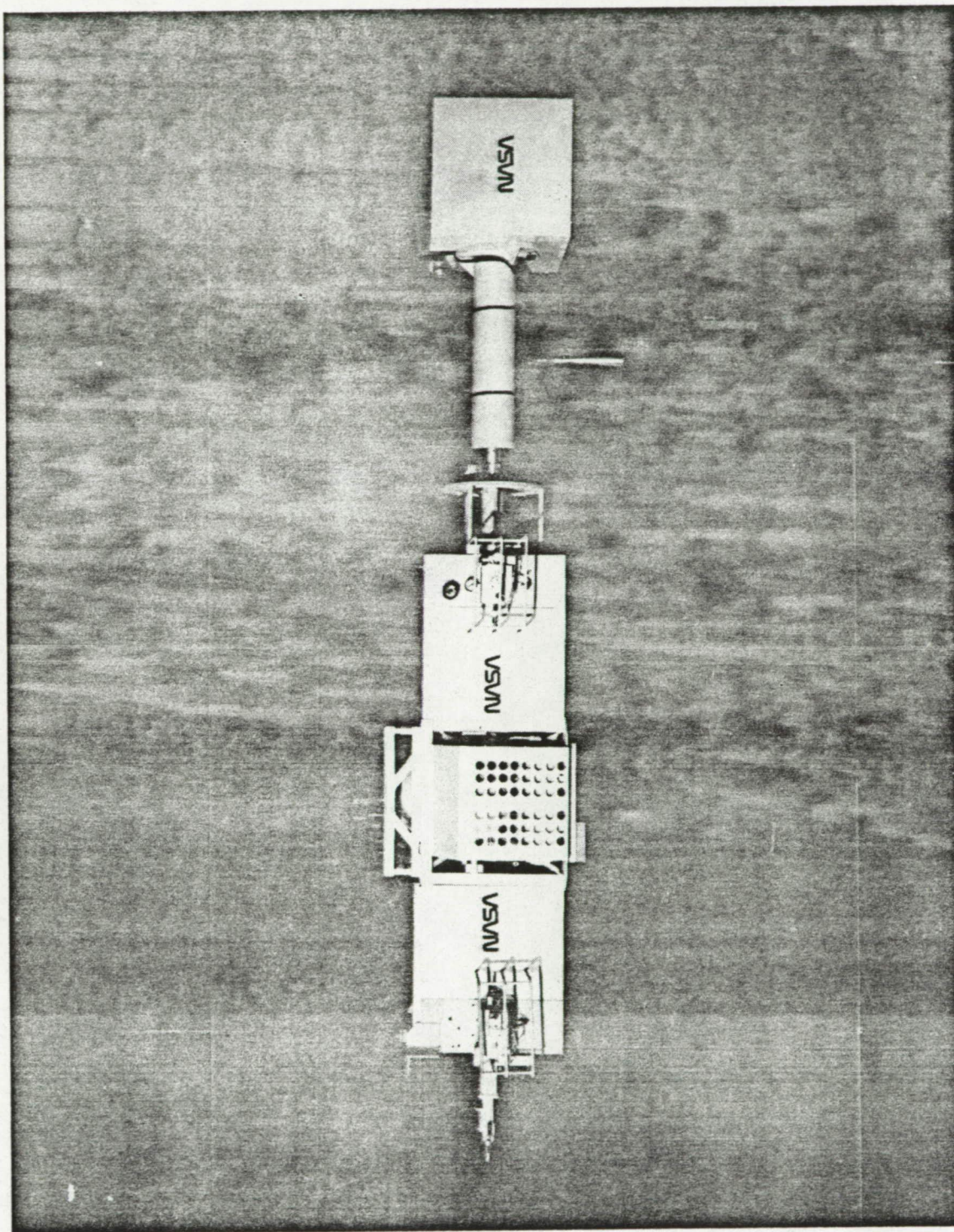


Figure 2-12: MU Hard-Docked with the DRM in Fully Latched Position

As previously mentioned, the TV camera was mounted on the DRM (see Figure 2-12). The camera, a Sony Corporation Model AVC 3400, had its 12.5-50 mm zoom lens manually set in a fixed position such that the DRM probe tip was visible across the full range of probe extension or retraction.

The simulation method employed for this test was similar to that described previously in this report, where the operator closed range and hard docked with a payload target. The DRM was in either a fully extended or fully retracted position, dependent upon the test condition.

A typical trial using the fully extended DRM condition began with the subject commanding the MU to close range until the forward latching assembly of the DRM entered the docking ring (Figure 2-13). Next, the subject enabled the latching mechanism, which secured the docking ring against the probe indexing ring (a soft dock), and simultaneously aligned the payload and DRM longitudinal axes. He then retracted the DRM until it mated with the probe docking ring and terminated the trial. The dependent measures were then recorded and the MU released and repositioned for the next trial. The same procedure applied for the fully retracted probe except that the trial terminated the trial. The dependent measures were then recorded and the MU released and repositioned for the next trial. The same procedure applied for the fully retracted probe except that the trial terminated after the operator fully latched the docking ring.

2.6.2.3 Experimental Design

The independent variables in the DRM evaluation were:

- DRM initial condition (capturing position)
 - fully extended
 - fully retracted
- Thrust mode
 - constant
 - trained.

The variables that were controlled during each test run were:

- MU - 3 DOF
- Test area lighting - two banks of two 1250 watt quartz iodide lamps
- Initial propellant pressure - $10.3 \times 10^6 \text{ N/m}^2$ (1500 psi)
- Battery voltage - 28 Vdc
- Initial range (MU docking ring to DRM tip fully retracted) - approximately 6.1 m (20 ft)
- Test surface - daily cleaning
- Subjects - four experienced subjects
- Latching probe - fully unlatched position
- MU/DRM alignment - boresighted.

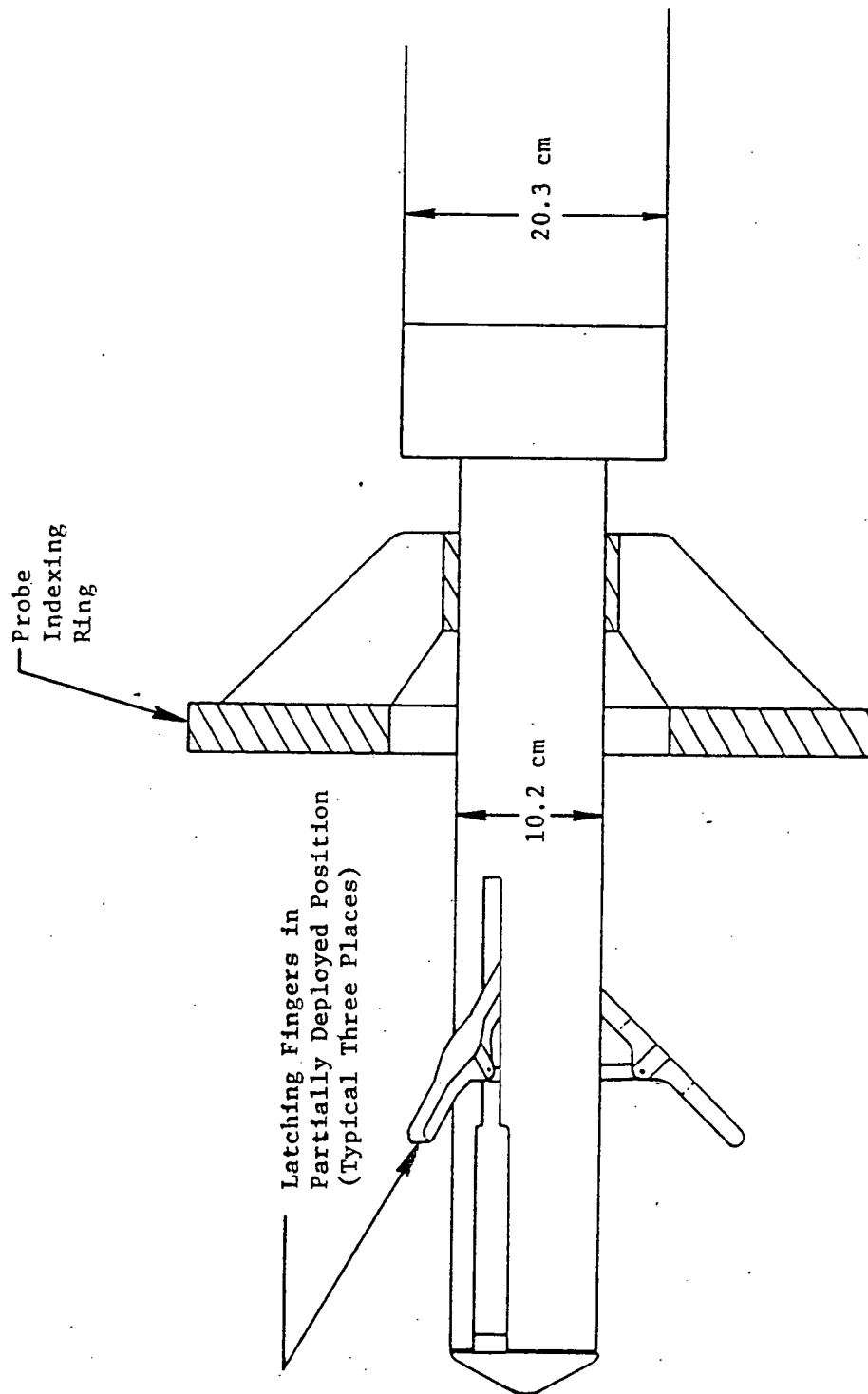


Figure 2-13: Forward Capture/Latch Assembly of the DRM

The dependent measures recorded after each trial were:

- Elapsed time
- Fuel consumed
- Aborted docking attempts.

2.6.2.4 Results and Conclusions

The two-hand controller concept was evaluated using the DRM to rendezvous and dock with a target payload. The testing involved two thrust modes and two DRM capture positions. The data were summarized and are presented as mean elapsed time vs test conditions in Figure 2-14 and mean fuel consumption in Figure 2-15.

The mean elapsed time averaged over all conditions revealed the two-hand controller concept resulted in longer elapsed times compared with the one-hand controller (121.6 seconds vs 80.8 seconds, respectively). In fact, the elapsed time for each condition was greater than for the corresponding condition using the single-hand controller.

The same pattern held true for fuel consumption where the overall mean value for the two-hand controller was 68 kg (150 psi) for the single-hand controller. Again, similar to the findings for elapsed times, fuel expenditure was greater for each test condition using the two-hand controller when compared to the single-hand controller concept.

The evaluation did show the feasibility of using a two-hand controller for performing rendezvous and docking maneuvers in the mobility laboratory. Also, post-test debriefings revealed that all subjects preferred the two-hand controller concept. However, performance data comparing the two-hand controller concept with the single-hand controller do not support this preference. Based on this statistical evidence, it appears that the two-hand controller should not be used with the DRM.

2.7 SOLAR MAXIMUM MISSION DOCKING SIMULATION

2.7.1 Purpose and Scope

The purpose of this test was to measure operator performance under two conditions of visual feedback on a rendezvous and docking task using a female satellite retrieval device (SRD) to dock with a target probe mounted on a Solar Maximum Mission (SMM) mockup.

Two configurations of camera location and docking target were investigated. The first configuration was a bore sighted camera mounted inside a drogue and in plane with a docking probe. The second configuration had a camera mounted on top of the MU and in plane with a double "V" docking target. This second configuration did not present visual feedback of the actual probe/drogue dock, whereas the first configuration did. The two concepts were tested in view of the fact that the SMM allows a limited docking envelope and that mounting a

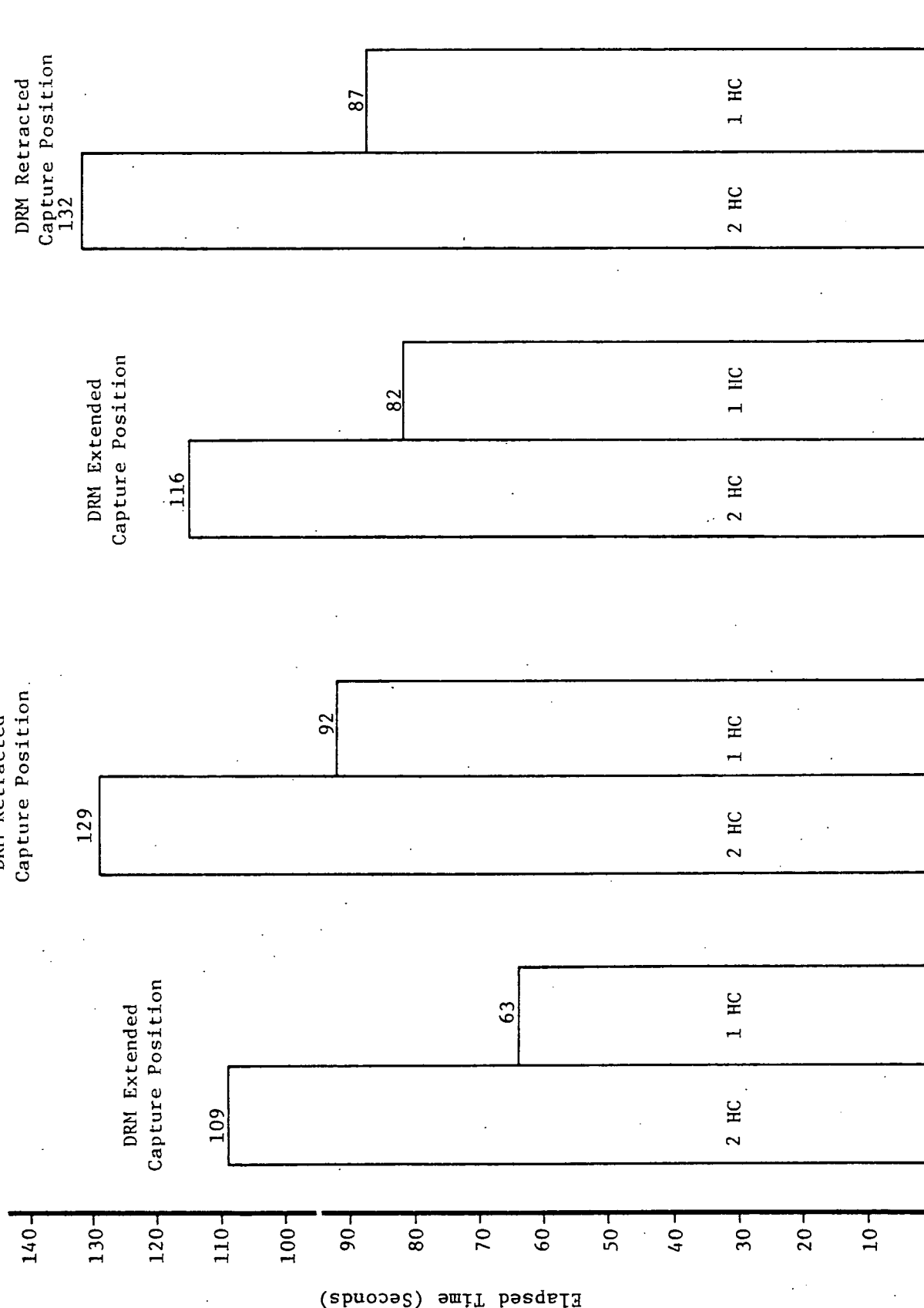
2 HC = Two-Hand Controller
 1 HC = Single-Hand Controller

DRM Retracted
 Capture Position
 132

DRM Extended
 Capture Position

DRM Retracted
 Capture Position

DRM Extended
 Capture Position



Constant Thrust Mode

Trained Pulse Thrust

Figure 2-14: Mean Elapsed Time for Two-Hand vs One-Hand Controller Using The DRM

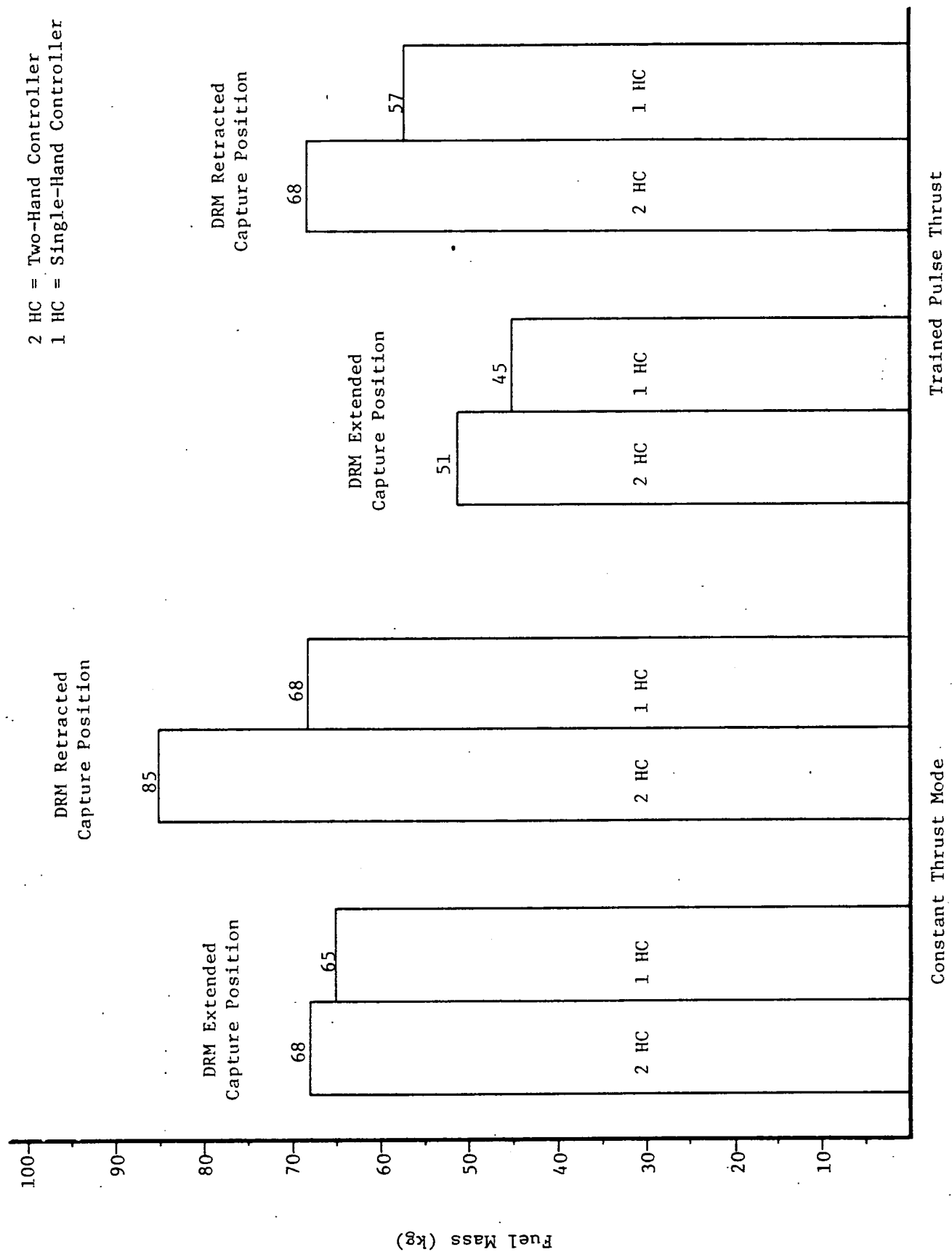


Figure 2-15: Mean Fuel Consumption for Two-Hand vs One-Hand Controller Using The DRM

camera inside a drogue causes a period of visual "blackout" during docking.

2.7.2 Test Apparatus and Methodology

The test apparatus consisted of: (1) a manipulator unit configured with two onboard cameras and a female satellite retrieval device located on the forward center section of the MU, and (2) a target satellite configured with a two-dimensional full scale mockup of the SMM.

MU Modification - The MU was modified by adding a top-mounted camera above and behind the SRD (see Figure 2-16). This camera (Sony Corporation, Model 3400 Vidiocorder) was set with a 0° offset relative to the forward face of the MU and in the horizontal plane corresponding to the SMM docking target. The other camera was the standard onboard camera used in previous tests this year. The SRD cylinder (43.2 cm long by 33 cm in diameter) projected in front of the center-mounted camera. The cylinder interior was painted flat black to reduce the glare to the camera. Clearance between the cylinder and the face of the MU was 19.7 cm.

The video link (Figure 2-17) was modified by transmitting the camera signals via a frequency combiner mounted onboard the MU and through a common antenna. The top-mounted camera transmitted via channel 2 VHF (54-60 MHz), and the center-mounted camera transmitted via channel 5 VHF (76-82 MHz). The telemetered signals were received in the operator's control room on a standard black and white TV monitor (Sony Corporation, Model CVM-115). The TV monitor could receive either channel 2 or 5 VHF.

SMM Mockup - The docking satellite, also used in previous tests, was modified by mounting a two-dimensional, low fidelity stiff foam and paper mockup of the SMM aft end without the high gain antenna (Figure 2-18). The mockup contained a 5 x 5 x 5 cm triangular-shaped wedge with a 23.5 cm standoff probe which served as the docking fixture for the SRD. Directly above this was mounted a 6.4 cm "V" shaped docking target with a 90.6 cm (16 in) distance. This was the docking target/aid for the top-mounted camera. Figure 2-19 depicts the MU in close proximity to the SMM preparing for a hard dock, and Figure 2-20 shows a hard dock between the MU/SRD and the SMM/probe.

The method employed in this test dictated that half the trials be conducted with the top camera/docking target and that half be conducted with the center-mounted camera/docking probe.

The procedure for each trial consisted of the operator maneuvering the MU to the SMM for a docking attempt (Figure 2-21). The operator made corrections in the MU's docking trajectory while attempting to maintain his docking target in the center of his TV monitor.

A successful dock was indicated by the MU/SRD's capture of the SMM docking probe and agreement of both the test engineer and test conductor that a successful dock had been completed. If a trial was aborted as indicated by the backing away and reestablishing a new trajectory, this was noted by the test

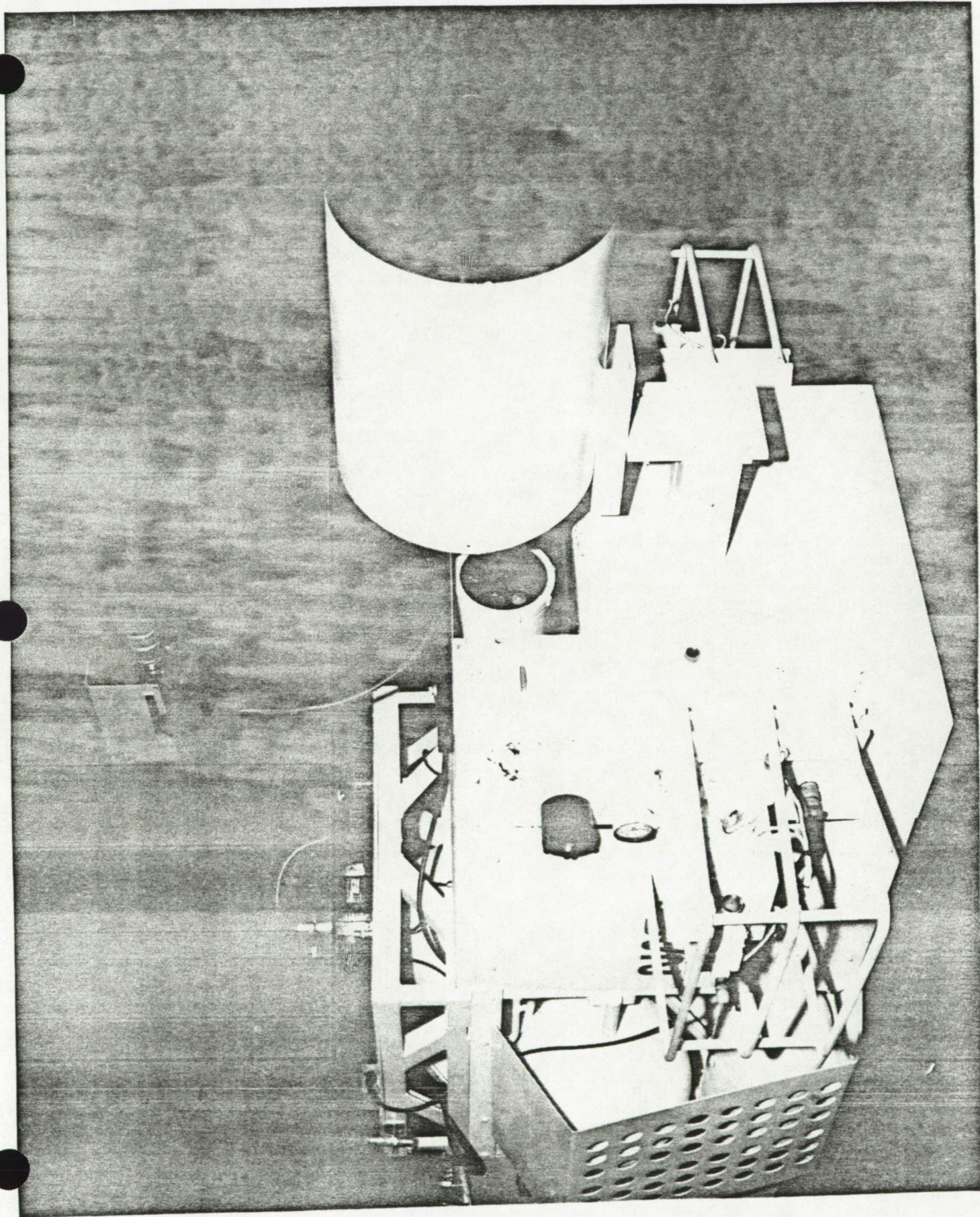


Figure 2-16: Mobility Unit Configured for SMM Docking Test

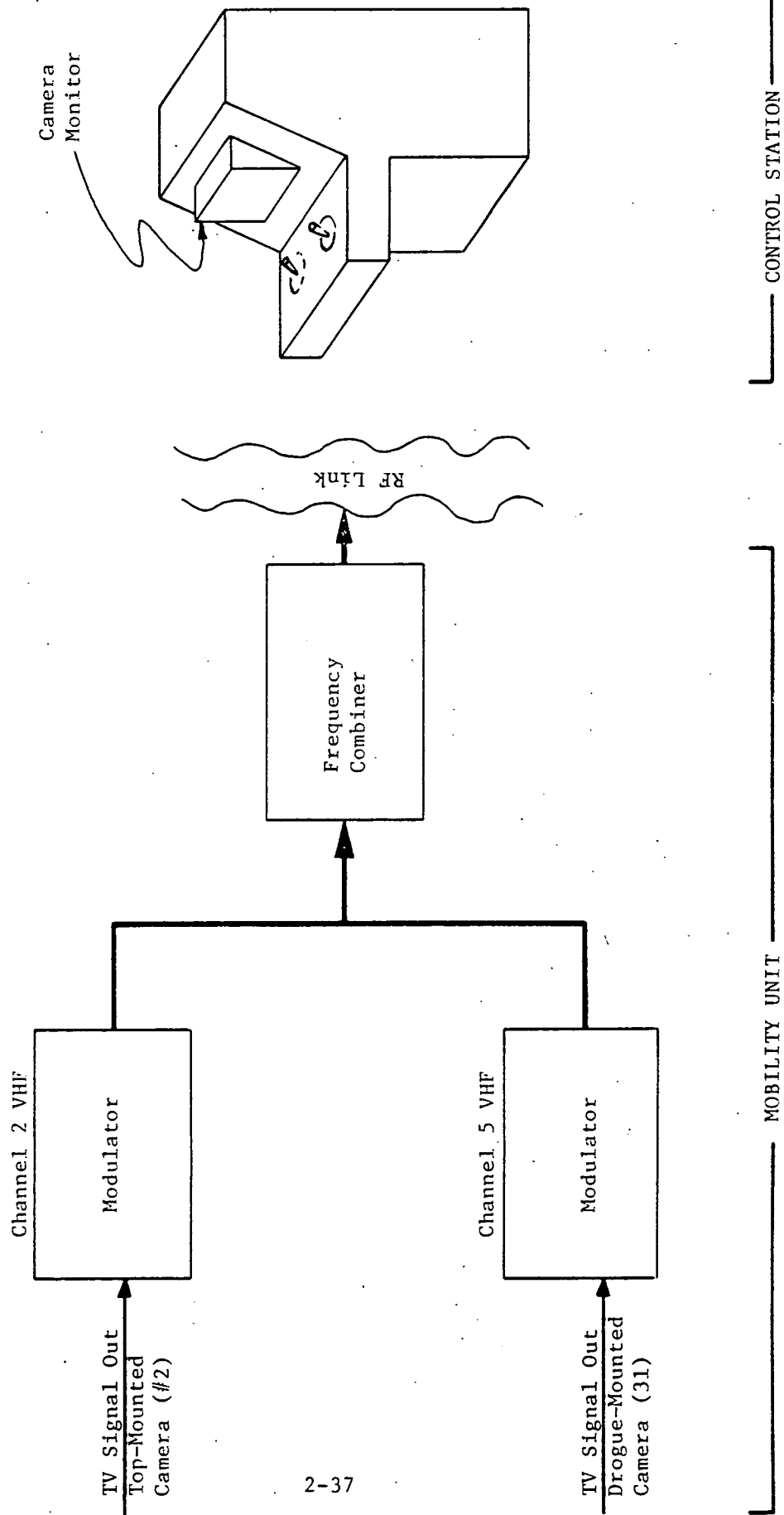


Figure 2-17: Video Link for SMM Tests

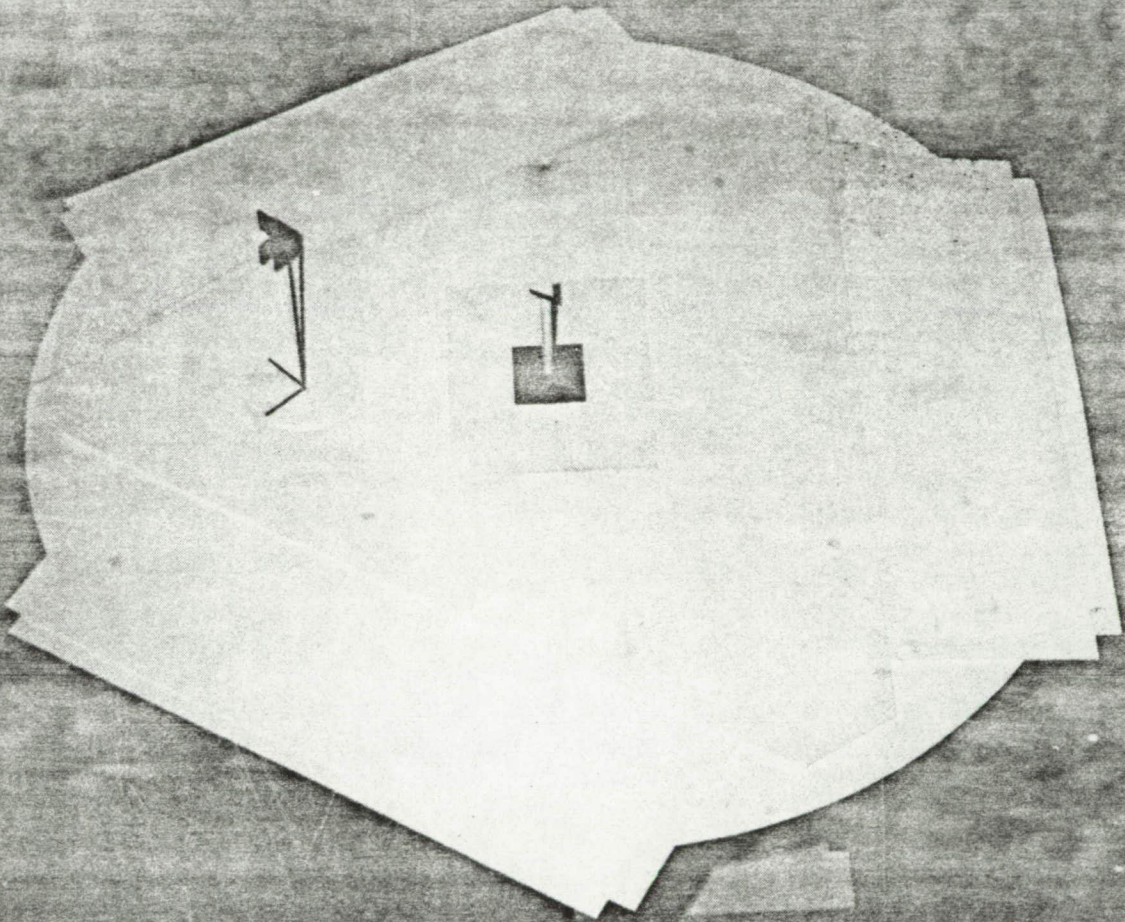


Figure 2-18: Docking Target Configured with SMM Mockup

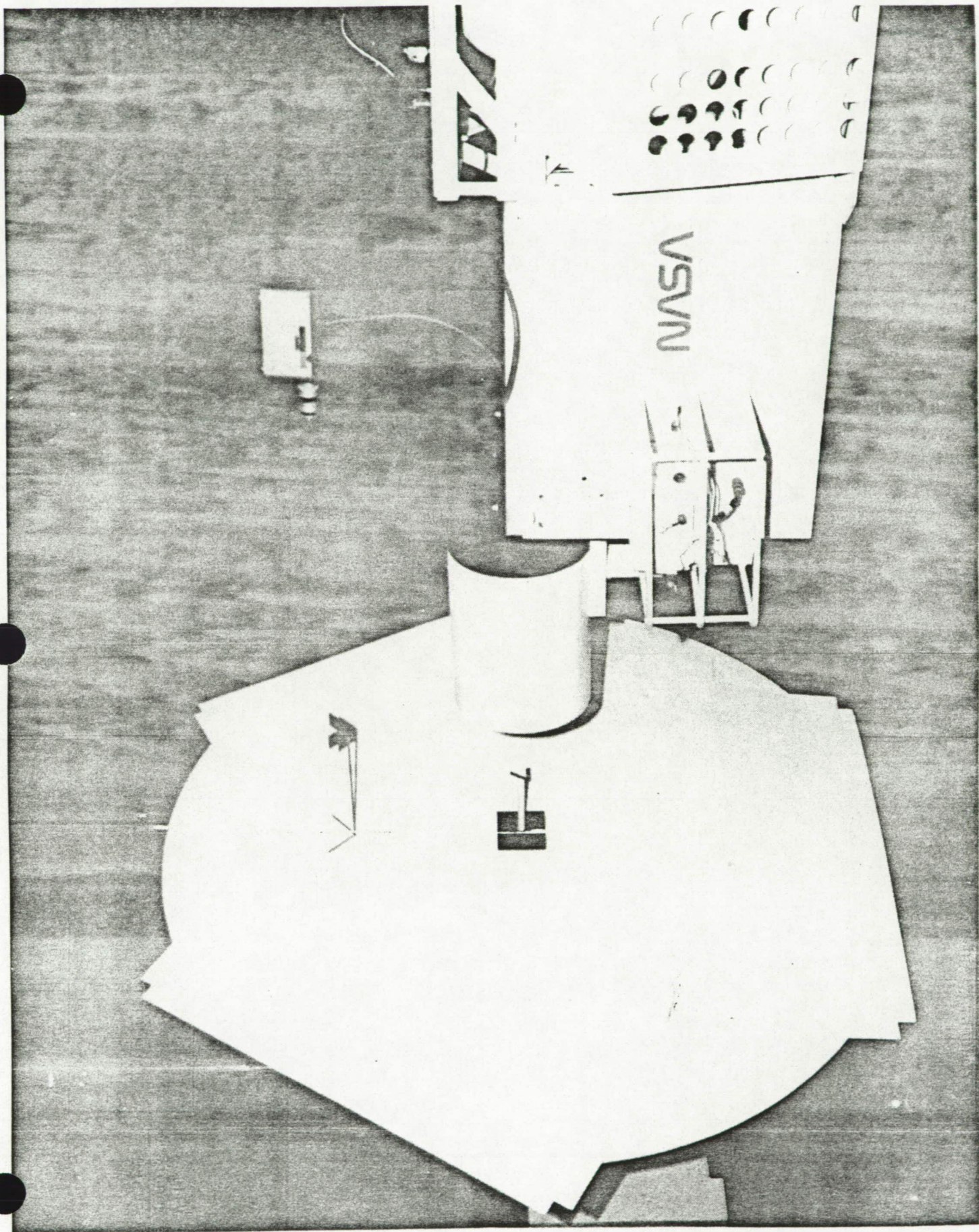


Figure 2-19: MU Preparing for Hard Dock with SMM

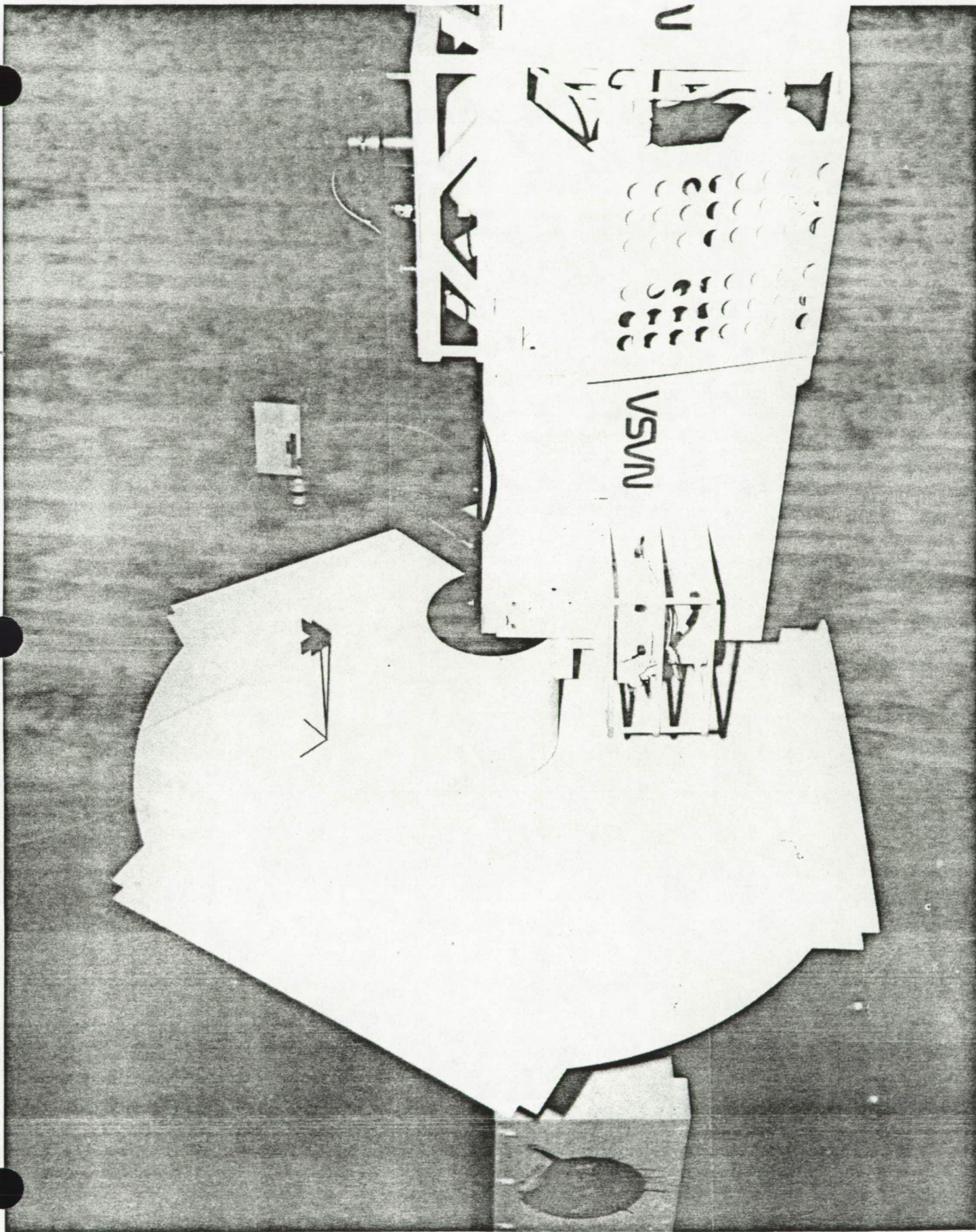


Figure 2-20: MU Hard-Docked with SM

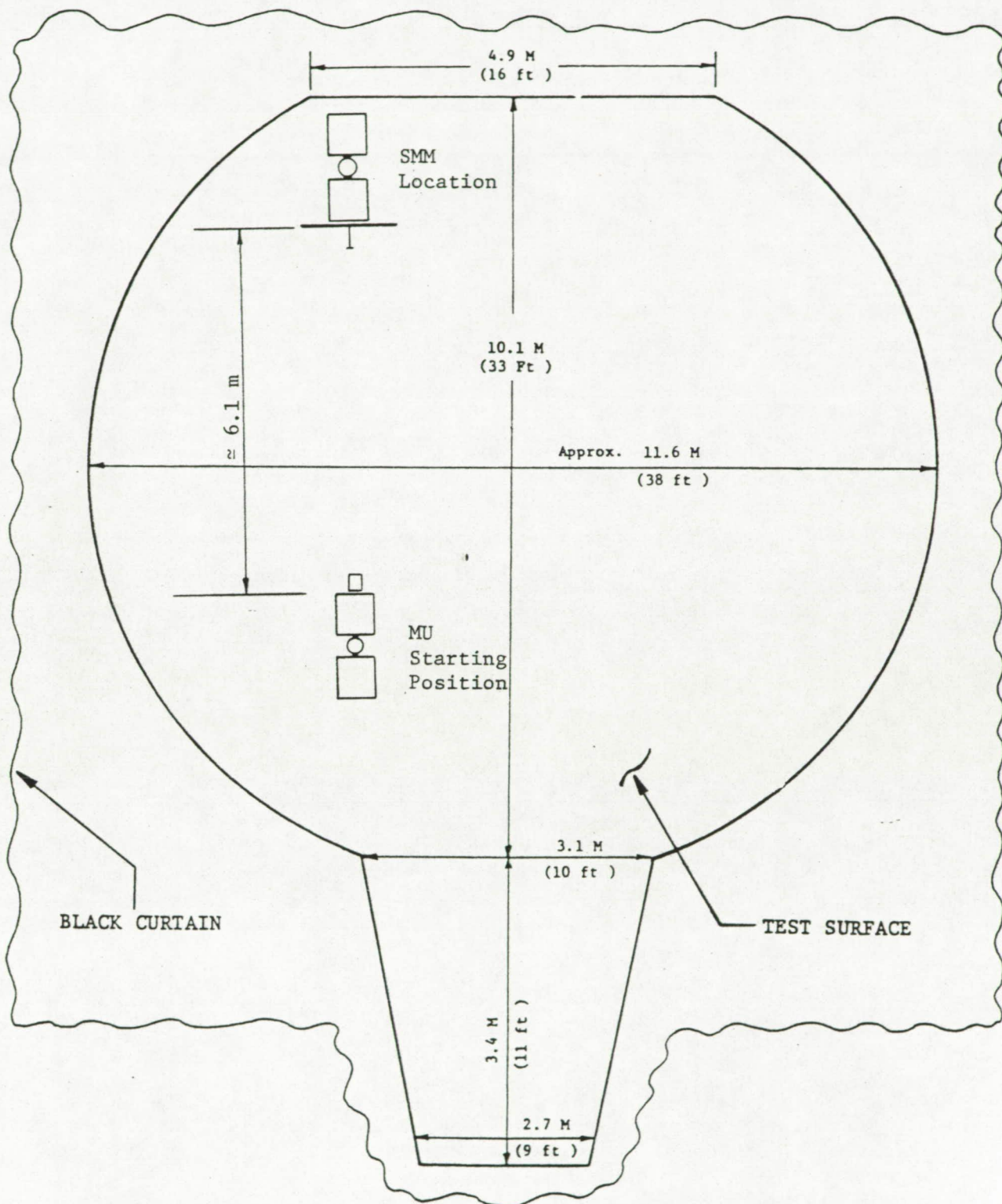


Figure 2-21: Mobility Laboratory Setup for SMM Test

conductor as an aborted run, as was a probe/drogue miss.

At the end of each trial, the dependent measures were recorded and a new trial was begun.

2.7.3 Experimental Design

The independent variables in the SMM test series were:

- Docking camera/docking target combination
 - top-mounted camera/"V" target
 - internally center-mounted camera/docking probe target.

Four subjects completed 30 docking trials under a counterbalanced order of presentation for the two camera/docking target conditions.

The control variables for this test were:

- MU starting position - ≈ 6.1 m (20 ft) from SMM
- MU/SMM attitude alignment - in plane and boresighted as indicated by TV feedback
- Test area lighting - two banks of two 1250 watt quartz iodide lamps
- Initial propellant pressure - 10.3×10^6 N/m² (1500 psi)
- Controller - two-hand
- Battery voltage - 28 Vdc
- Operator's TV monitors - daily check for high quality picture
- Initial position of SMM - far edge of floor
- Test surface - daily cleaning
- Subjects - four experienced subjects completing 60 trials each
- Thrust mode - trained pulse at 5.5 pulses/second.

The dependent measures recorded during each test were:

- Elapsed time for docking
- Fuel consumed for docking
- Number of aborts/misses.

Elapsed Time for Docking - The time required for docking is an obvious figure of merit for system/operator performance. Presumably, the longer the time required, the greater the difficulty of the tasks associated with a particular test condition. In addition, studying completion time as a function of the independent variables employed permits detection of differential effects on these variables on different tasks. For example, attitude control system effects would be expected during the final approach to a greater degree than during initial translation. Furthermore, completion time data will be required for mission timeline planning and workload analysis. If task completion were time constrained during a mission, such data could be used to analyze the probability of task completion in connection with reliability analyses.

Fuel Consumed for Docking - The considerations which were stated in connection with completion time also apply to fuel consumption. This measure serves as a performance figure of merit, particularly since errors in aligning the MU and SMM will require correction which will be reflected in increased fuel expenditure. Data on distributions of fuel required will also be useful in determining system design requirements.

Number of Aborts/Misses - The number of test aborts/misses was recorded, and this information was stored for possible future use.

2.7.4 Results and Conclusions

The mean time to complete a rendezvous and docking maneuver using the center-mounted camera was 89.75 seconds while the mean time using the top-mounted camera increased to 94.3 seconds.

Mean fuel consumption when using the center-mounted camera was 36.9 kg (81.5 psi) and when using the top-mounted camera was 38.5 kg (85.0 psi).

The raw data were subjected to a three way analysis of variance with all factors fixed except subjects. The resulting source tables are presented for the two dependent measures, elapsed time and fuel consumption (see Table 2-5 and Table 2-6).

The analysis of variance for elapsed time showed no significant main effects or interactions.

The analysis of variance for fuel consumption showed the main effect of camera location reached a level of statistical significance ($P < .01$), and these data are presented in Figure 2-22. The data indicate the center-mounted camera/docking probe condition consumed less fuel and also required a shorter elapsed time to dock. It is felt that this may be due in part to the fact that the center-mounted drogue camera was transmitting a clearer picture to the operator's station. In order to improve the top-mounted camera's signal, a second monitor was located outside the control room, and the output from this was hardwired into the subject's monitor. In effect, the receiving antenna was moved. Another problem for the operator which was caused by the quality of the signal from the top-mounted camera was that, when in close to the "V" target, the operator could not discriminate his closing angle. Therefore, when he attempted to center his docking target, the position commands generated increased the angular disparity and consumed more fuel when the operator attempted to reestablish a straight-in dock.

Table 2-5: Analysis of Variance for Time
Source Table

SOURCE	df	SUM OF SQUARES	MEAN SQUARE	F
Mean	1	2032645.0	2032645.0	462.3
Subjects (S)	3	13190.5	4396.8	-
Camera (C)	1	1246.7	1246.7	5.96
Trial (T)	29	27518.1	948.9	1.37
SC	3	627.5	209.2	
ST	87	60274.2	692.8	
CT	29	16309.5	562.4	1.25
SCT	87	39160.2	450.1	

Table 2-6: Analysis of Variance for Fuel Consumption
Source Table

SOURCE	df	SUM OF SQUARES	MEAN SQUARE	F
Mean	1	1662469.0	1662469.0	107.5
Subjects (S)	3	46382.2	15460.5	-
Camera (C)	1	752.6	752.6	45.6**
Trial (T)	29	35544.2	1225.6	.8
SC	3	49.5	16.5	-
ST	87	132752.6	1525.9	-
CT	29	48544.2	1673.9	1.40
SCT	87	104088.3	1196.4	

**Significant at the .01 Level

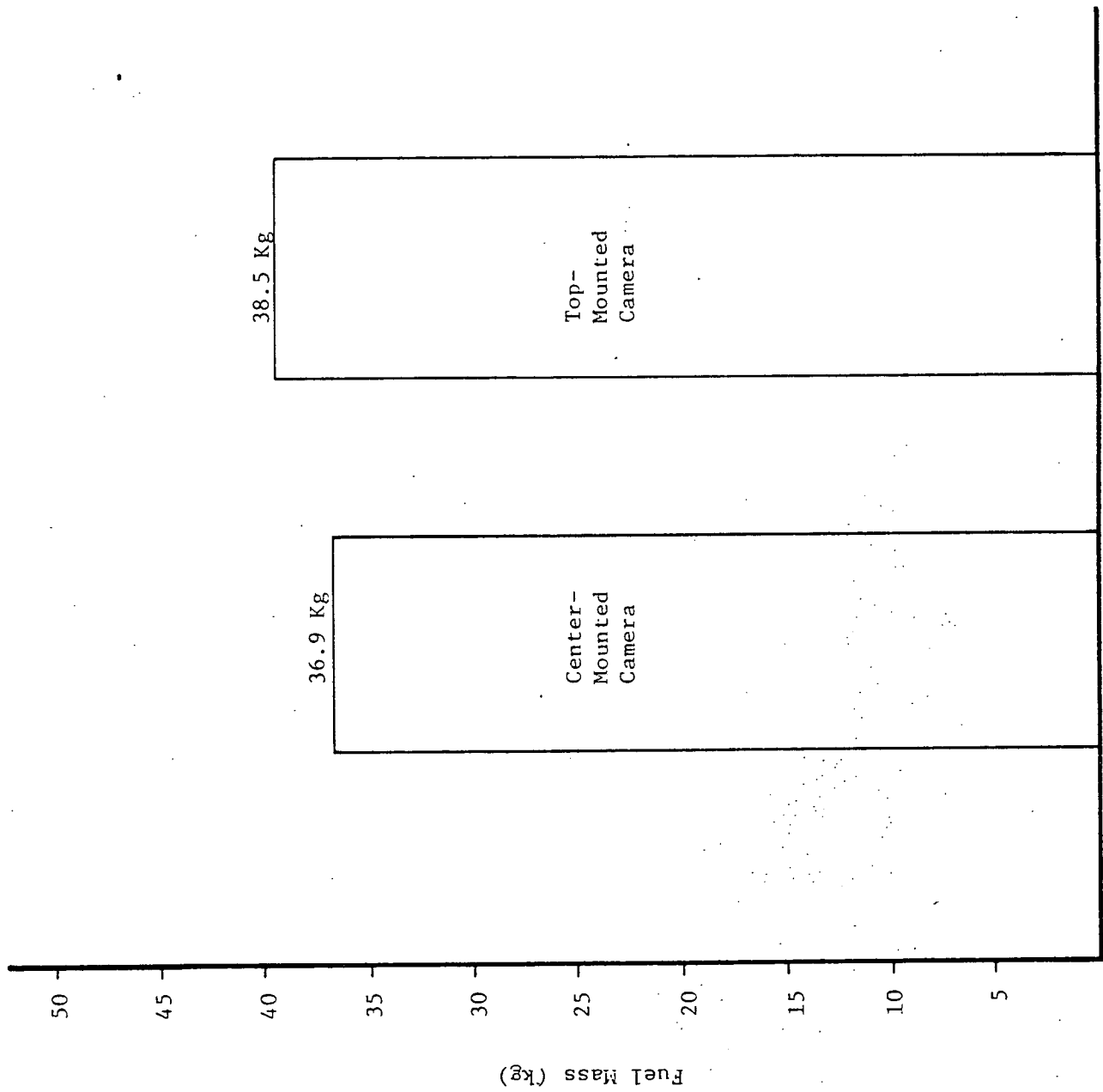


Figure 2-22: Fuel Consumption as a Function of Camera Location

3.0 MANIPULATOR SYSTEM EVALUATION LABORATORY

During 1978, Essex research and facility development activities in the manipulator laboratory were planned around the following goals:

- Conduct manipulator evaluation tests on the Protoflight Manipulator Arm (PFMA)
- Conduct hand controller selection/evaluation tests to determine the optimum controller concept
- Develop various software schemes for evaluation with the PFMA and hand controller hardware, in particular using previously derived control laws as well as Essex-generated control concepts
- Conduct end effector trade off evaluations to determine the optimum end effector for different on-orbit tasks.

The ultimate goal of these activities was to develop operational performance data for several combinations of hardware and software to be used in performing various tasks using the PFMA in simulated on-orbit tasks.

In addition to these tasks, Essex was involved in several engineering studies during the year. These studies were undertaken using the PFMA as a testbed for proposed refinement and improvement to the basic hardware concepts. The two studies undertaken were to:

- Determine whether the PFMA/controller(s) as currently configured are capable of manipulating standard off-the-shelf hardware or if special purpose hardware must be designed and fabricated
- Improve manipulator range/range rate determinations through the use of a National Bureau of Standards (NBS) proximity sensor.

Work on these tasks proceeded throughout the year as described below.

This section contains a description of the laboratory facility and test equipment, a list of major research questions, how resources were utilized during the year, and a discussion of 1978 test accomplishments.

3.1 FACILITY DESCRIPTION

The Manipulator System Evaluation Facility provides the laboratory space and testing hardware necessary to collect quantitative data on manipulator systems, hand controller concepts, and software applications. The primary

elements of the facility are:

- A Protoflight Manipulator Arm (PFMA) with associated hand controller(s), computer interface subsystems, and visual feedback subsystems
- Task board(s) to simulate typical servicing and/or assembly tasks
- Remote operator and experimenter stations that provide all controls and displays necessary for a test subject to perform actual tasks with the PFMA and for an experimenter to monitor those tasks
- An experimenter's station that provides an interface to the task board hardware
- An electronic digital computer interfaced to the hand controller(s) and PFMA to interpret the commands given by a test subject and to drive the PFMA.

Three rooms are utilized for manipulator testing: the manipulator high bay; the control room; and the SEL 840A computer room. Several changes have been made to the facilities since the previous year's report was published. These changes are outlined below. For descriptions of the earlier facility configurations, see Reference 3. The current major equipment and physical layout of these rooms are shown in Figures 3-1 through 3-4.

3.1.1 Manipulator High Bay

The manipulator room contains the PFMA along with its support equipment (lights, cameras, task board(s), and electronic interfaces). The experimenter's station is located near the computer interface panel so the conductor's assistant can record times, distances, errors, etc., as well as have an unobstructed view of the arm to make adjustments and be able to initiate power down procedures in an emergency situation. The task board(s) are located such that the test subject can see only one board at a time when viewing the control room monitors. Also, the experimenter's assistant has easy access to the task boards for setup and adjustments.

The manipulator room also contains three mono-video cameras with the capability of having the experimenter monitor one of the video scenes so the scene presented to the operator is also available to the experimenter in the manipulator room. The current camera configuration consists of two Telemation floor-mounted cameras with zoom lenses, one on either side of the PFMA, and a Westinghouse fixed focus, fixed diaphragm solid state camera mounted directly on the arm at the elbow and adjusted for viewing the end effector in its nominal position.

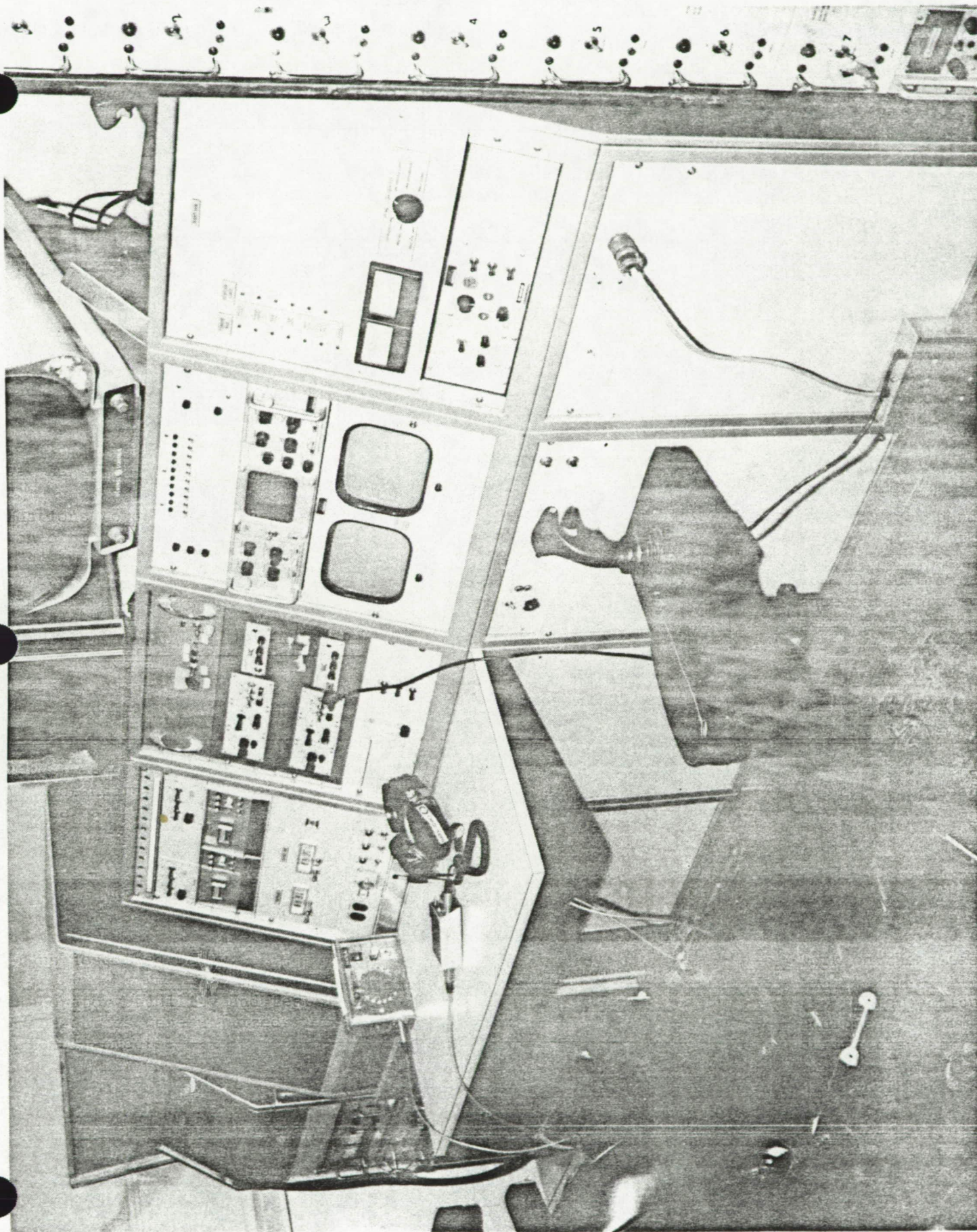


Figure 3-1: Control Room

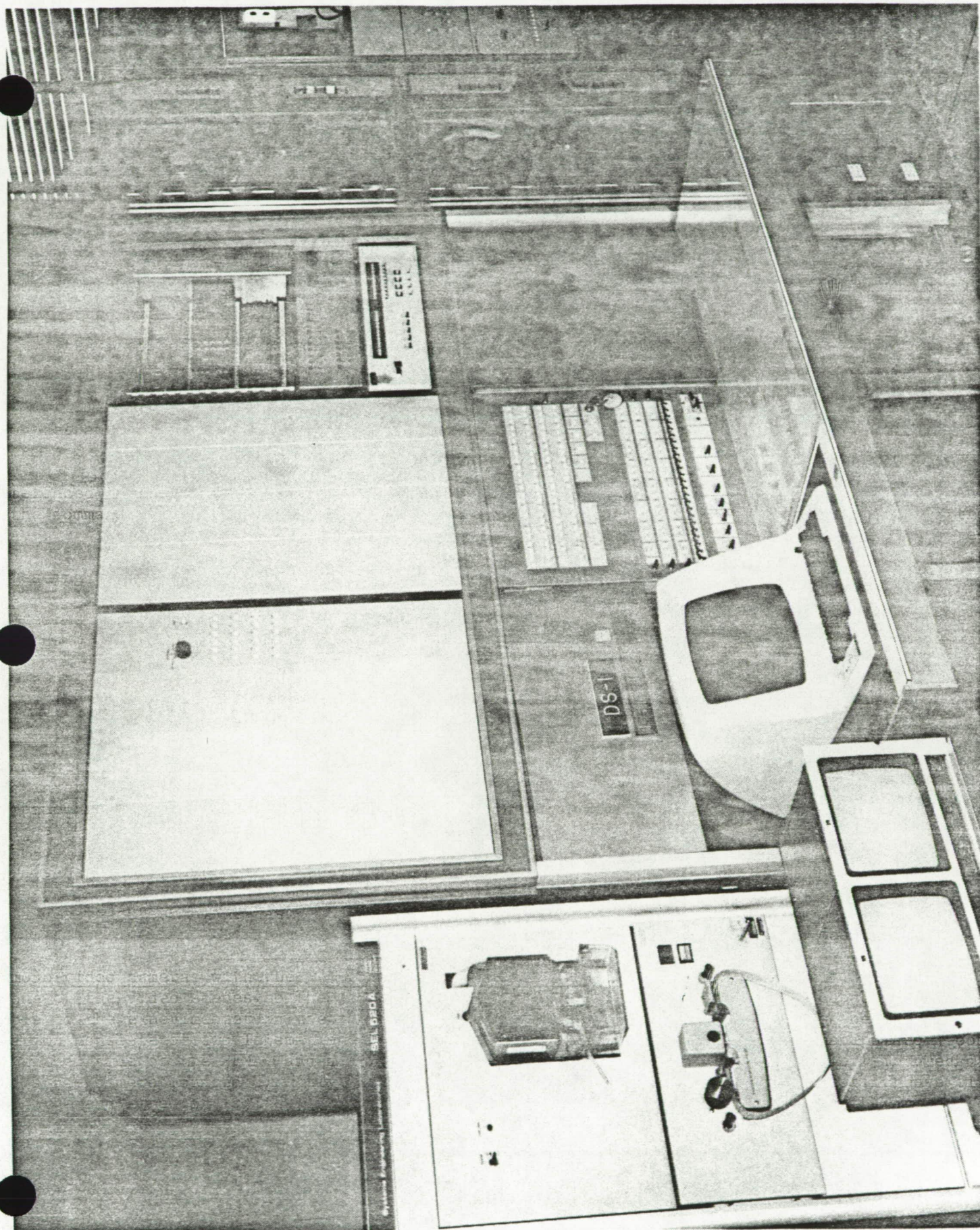


Figure 3-2: SEL 840A Computer Room

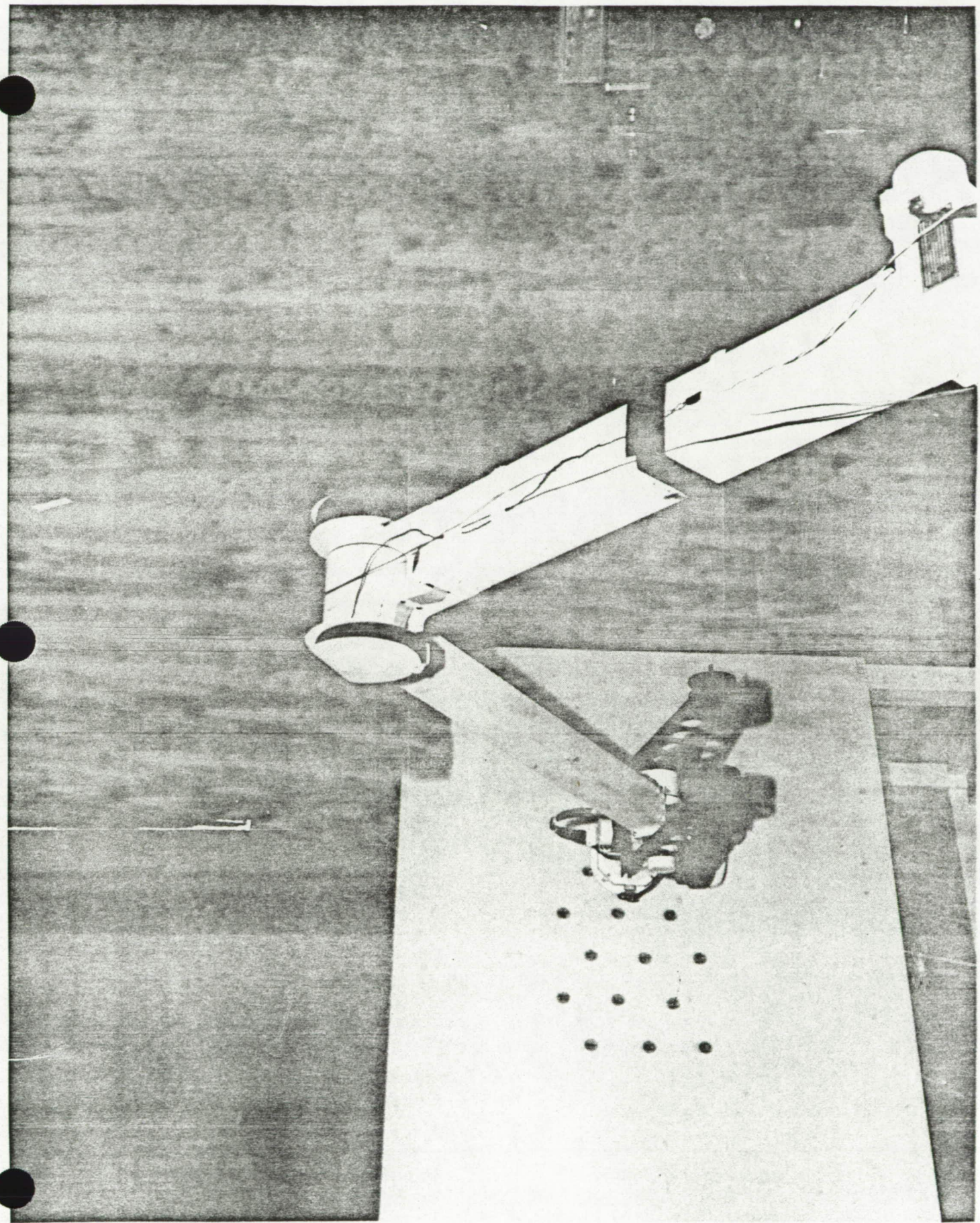


Figure 3-3: Manipulator Room Showing PFMA and Training Task Board

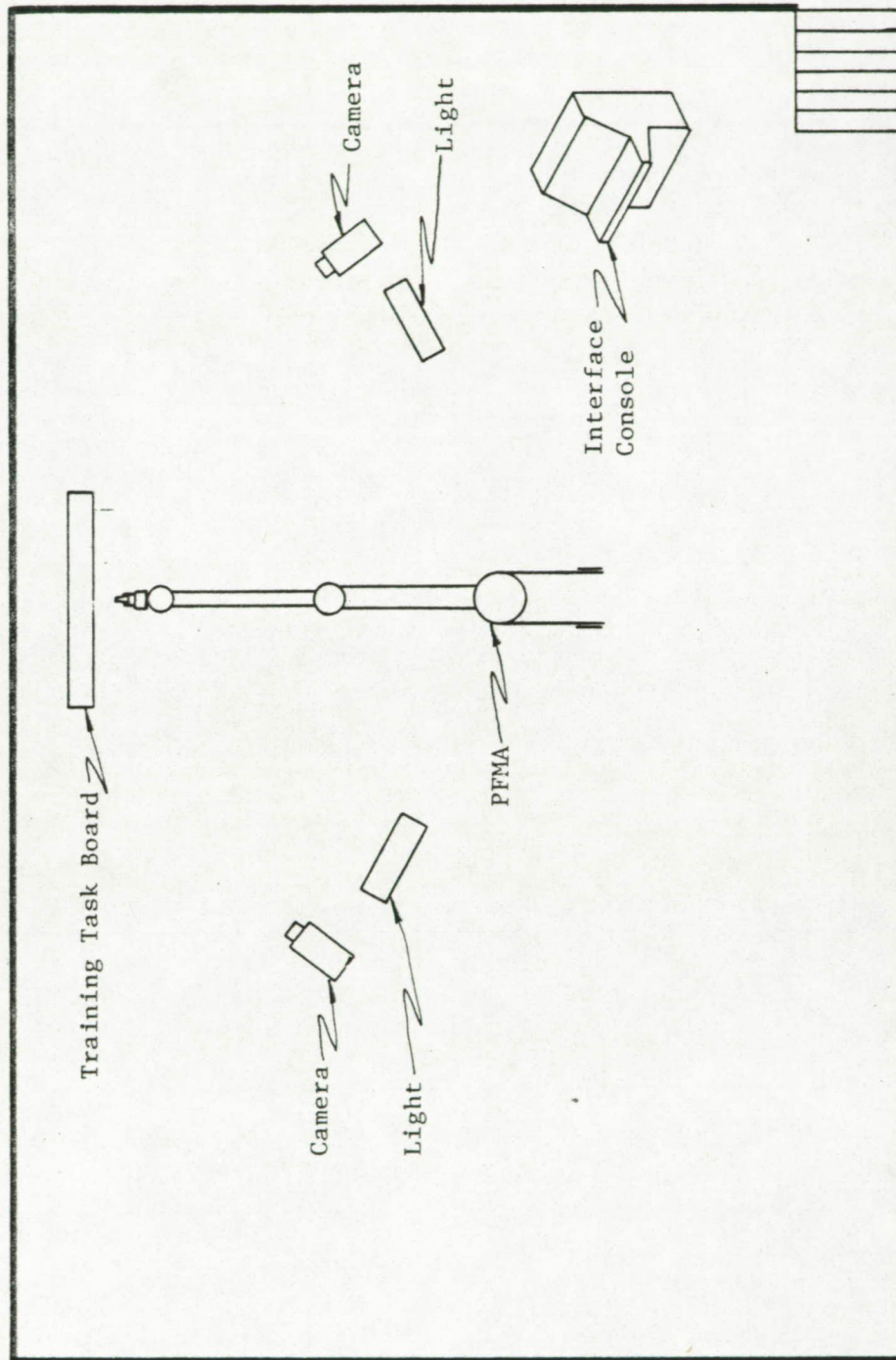


Figure 3-4: PFMA Room Layout

3.1.2 Control Station

The control room contains the operator and experimenter workstations, from which communications between the experimenter and his assistant are maintained via headsets. From the control room, the experimenter can maintain visual observation of the test subject and can control the PFMA in emergency situations. The operator's station consists of one of the hand controllers and the video monitors for two of the three cameras in the manipulator room. The third monitor is screened from the operator so the experimenter has a view of the overall activity in the manipulator room. The current monitor configuration consists of two 9-in CONRAC rack mounted video monitors, one with input from one of the Telemation cameras, and the other with input from the Westinghouse camera mounted on the PFMA elbow. The experimenter's monitor is a 19-in monitor mounted above the console rack and screened from the subject's view during testing.

3.1.3 Computer Room

The computer room contains a SEL 840A computer along with peripheral equipment as well as part of the interface electronics (A/D and D/A converters) so the operator may control the PFMA and the computer can maintain information on the arm's position and movements.

3.1.4 Facility Changes

During 1978, the PFMA was moved from the A wing of Building 4487 to a high bay area behind A wing, where other NASA manipulator hardware is also located. To facilitate this move, cables were fabricated to provide the length necessary to link the control room with the new manipulator room. It was determined that the video system used in prior years could not be used in the new facility because of the difficulty of obtaining or fabricating adequate cabling. For this reason, the Telemation video hardware was used. Using the Telemation video equipment also provided an audio link between the control room and the manipulator room without the necessity of obtaining new hardware.

3.2 TEST EQUIPMENT DESCRIPTION

The major equipment used in the Manipulator Laboratory during 1978 consisted of the video system, the PFMA, the hand controllers, and the SEL 840A computer. These elements are described below.

3.2.1 PFMA Video System

The video system and associated equipment used with the PFMA manipulator are comprised of the following subsystems:

- TV cameras (3) - two remotely controlled Telemation, Inc., Model TVC-2100 and one Westinghouse, Model 130
- Telephoto zoom lens (2) - Pelco, Inc., Model TV-V10X15 (drives) with Canon Camera Co., Inc., Model V10X15, f.1. 15-150mm (lenses) on the Telemation cameras

Key
 μ = yaw
 θ = pitch
 ϕ = roll
 s = shoulder
 e = elbow
 w = wrist
 I = upper arm (index)

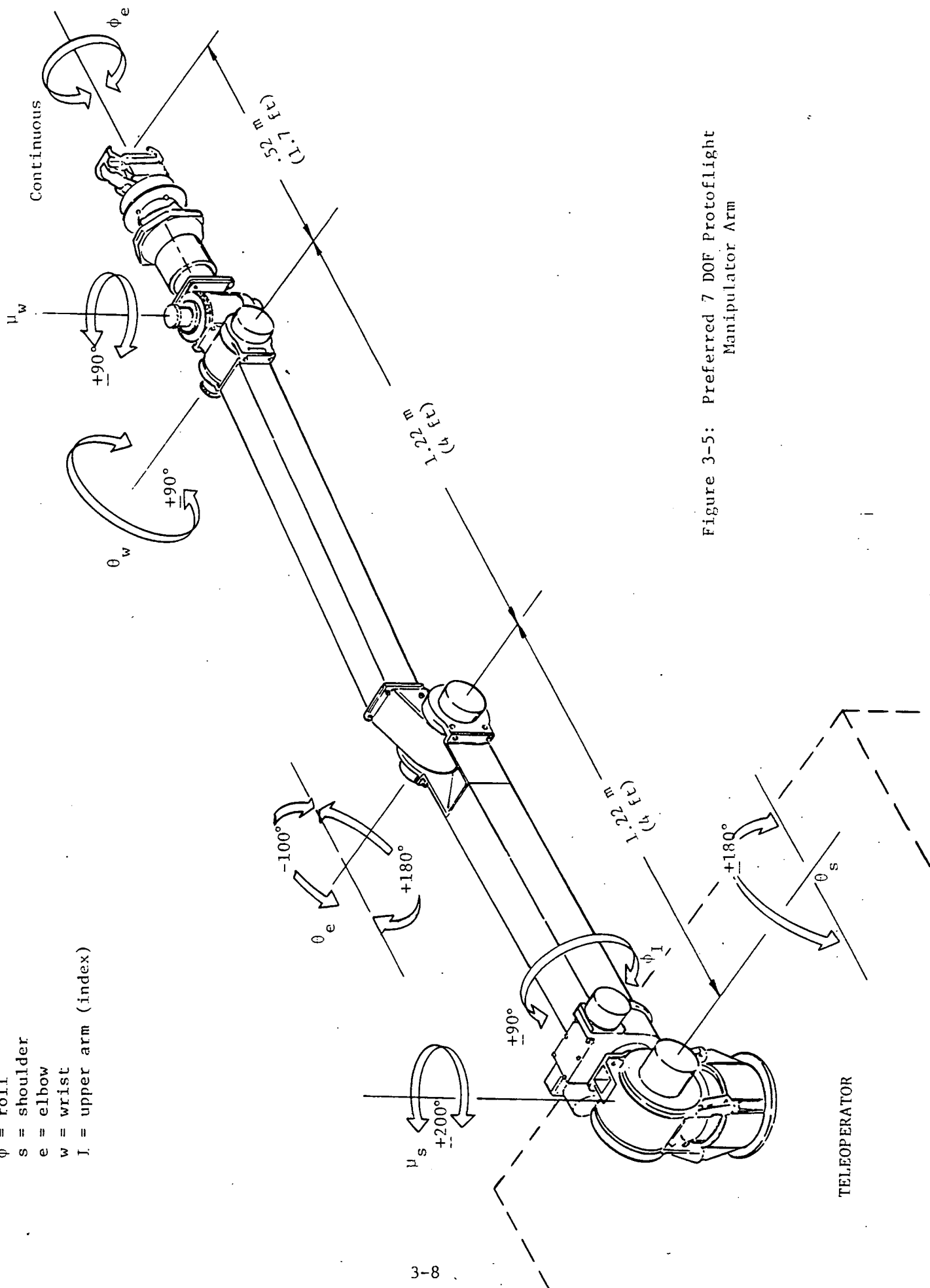


Figure 3-5: Preferred 7 DOF Protoflight Manipulator Arm

- Pan and tilt units (2) - remotely controlled, Pelco, Inc., Model PT-550M
- Tripods (2) - Hercules, Inc., Model 5450 for Telemation cameras
- 8-in diagonal black and white TV monitors (2) - Conrac Model CNB8
- Camera Remote Control Panels (2) - Cohu Electronic, Inc.

The display system used for this program consisted of three independent closed circuit TV systems. All TV equipment was of the commercial, "off the shelf" variety. The Telemation cameras were located at 45° angles with respect to the task board and arm, and the Westinghouse camera was mounted on the PFMA at the elbow. The right hand camera presented a view of the target from the right and was therefore displayed on the right monitor. The left hand camera presented a view of the target from the left and was displayed on the overhead monitor for the experimenter. The Westinghouse camera had a head-on or normal view of the target. The end effector was viewed by the subject on the left monitor.

3.2.2 Manipulator Arm

The manipulator arm evaluated during 1978 was a modular, six degree-of-freedom, Protoflight Manipulator Arm (PFMA). The PFMA was designed for use on the teleoperator for such tasks as satellite servicing and space structure assembly.

The PFMA shown in Figure 3-3, above, is an anthropomorphic manipulator assembly having flexible joints for shoulder, elbow, and wrist. The shoulder is capable of movements in the pitch and yaw axes. The elbow is capable of pitch movement, with roll/indexing capability between the shoulder and elbow. The wrist assembly provides roll, pitch, and yaw positioning for the end effector. The reach of the entire manipulator is in the range of 25 cm (10 in) minimum to 200 cm (96 in) maximum measured along a line from the shoulder pitch axis to the wrist pitch axis. Total arm length including wrist and end effector is 3.05 m (10 ft). The indexing motion extends coverage to an approximate hemispherical shape over the grasping interface. Each joint consists of one or more 28 Vdc reversible motors, and movement is accomplished through a system of gears and/or clutches. The operating characteristics are given in Table 3-1. Movement is possible along the axes shown in Figure 3-5. At full extension, the arm has a tip force of 44.5 N (10 lbs).

The end effector assembly is also driven by a 28 Vdc drive system with grip depth of at least 8.9 cm (3.5 in), grip speed 3.8 cm/sec (1.5 in/sec), and grip force from 44.5 N (10 lb) to 397 N (89 lb). The current end effector has a parallel jaw operation which is driven through a spiroid gear set.

A servo electronics package is necessary to establish an interface between the SEL 840A and the PFMA. This package interfaces the power supplies for the various joints, along with calibration circuits for adjusting the minimum voltages (brake voltage) for the joints. It also provides a selection

Table 3-1: PFMA Operating Characteristics

	<u>Max. Possible Displacement</u>	<u>Rate (Max)</u>	<u>Motor Torque</u>
<u>SHOULDER</u>			
Pitch	$\geq 180^\circ$	11.5°/sec	123 N-m (90 ft-lbs)
Yaw	$\geq \pm 200^\circ$	11.5°/sec	123 N-m (90 ft-lbs)
<u>UPPER ARM</u>			
Roll/Indexing	$\geq \pm 90^\circ$	11.5°/sec	9.5 N-m (7 ft-lbs)
<u>ELBOW</u>			
Pitch	$\geq + 180^\circ$ $\geq - 100^\circ$	23°/sec 23°/sec	68 N-m (50 ft-lbs) 68 N-m (50 ft-lbs)
<u>WRIST</u>			
Pitch	$\geq 90^\circ$	11.5°/sec	20.5 N-m (15 ft-lbs)
Yaw	$\geq \pm 90^\circ$	11.5°/sec	20.5 N-m (15 ft-lbs)
Roll	Continuous	11.5°/sec	20.5 N-m (15 ft-lbs)

capability to enable the operator to select either rate or position feedback information from the arm. In its current configuration, it is not possible to obtain maximum grip force from the end effector from this interface. Approximately 134 N (30 lbs) is all that is obtainable at present. To increase this would require a separate, higher current power supply for the end effector alone. An area which was studied was whether or not the current grip force was sufficient for test and evaluation purposes.

In using the servo electronics package to move the PFMA, the sequence of power application, beginning with the operator, is as follows:

The operator activates the hand controller which, in turn, provides information to the computer. The computer then activates the appropriate circuit in the servo electronics package. That circuit moves the desired joint on the arm. The feedback circuits provide information from the arm back to the computer in order to indicate the rate of movement or the position of the arm.

When the entire servo electronics package is installed, velocity and position will be indicated through the feedback circuits by means of voltage variations which translate to show the distance and the angle of deflection through which the arm has traveled from a reference point. This will enable

the computer software to determine the location of each joint.

At present, NASA has installed the rate feedback circuits in the interface package. Feedback on position is not currently available. When the position feedback hardware has been installed, the operator, at any given time, will have access to either rate or position information, but not both simultaneously. This is because the design of the interface allows only one set of information to be transmitted to the computer at a time.

3.2.3 Hand Controllers

Prior to the 1978 contract year, it was determined that one of the three hand controllers (MIT SD-2) originally scheduled to be evaluated would be eliminated from consideration. The MIT SD-2 had too much cross talk to provide fine enough control of the PFMA after the effects of the cross talk had been eliminated through deadbands, etc.

The two hand controllers which were considered during 1978 were the Measurements Systems, Inc. (MSI)-544 and the MSI-404, which are described in the paragraphs below. Both the MSI-544 controller and the MSI-404 controller were delivered with the major electronics contained within the controller. Power supplies, voltage dividers, and other additional hardware had been designed and fabricated by Essex during previous contract periods.

3.2.3.1 MSI-544 Hand Controller

The MSI-544 controller, along with the additional hardware, is schematically depicted in Figure 3-6. As may be seen in this figure, Switch A and Switch B were connected across a voltage divider with ± 6 volts applied to either end of the divider. The 20K ohm potentiometer allows adjustment of the input to A/D 31 to provide zero volts when neither switch is activated. When either Switch A or Switch B is closed, one of the 10K ohm resistors is shorted, thereby generating zero, negative, or positive voltages into A/D 31 to indicate the three possible states. The trigger is connected in a similar manner without the zeroing potentiometer. Depression of the trigger to each of the two detents provides A/D 30 with a different voltage to indicate the state of the trigger. The four-axis control electronics were provided in the controller housing itself. All that was necessary for operation was provision of ± 15 volt power supplies and connection to the appropriate A/D converters. The two-axis, thumb-operated control stick, although installed in the controller, did not include the load resistor potentiometers necessary for developing the output control voltages and for zeroing the control signals. These were added, and the signals were output to A/D 25 and A/D 26.

3.2.3.2 MSI-404 Hand Controller

The MSI-404 controller, shown in Figure 3-7, was connected in the same manner as the previously described MSI-544 controller as far as Switches A and B and the trigger are concerned. The load developing and zeroing potentiometers for the two-axis, thumb operated control stick were included within the controller for this model, and, therefore, it was only necessary to connect

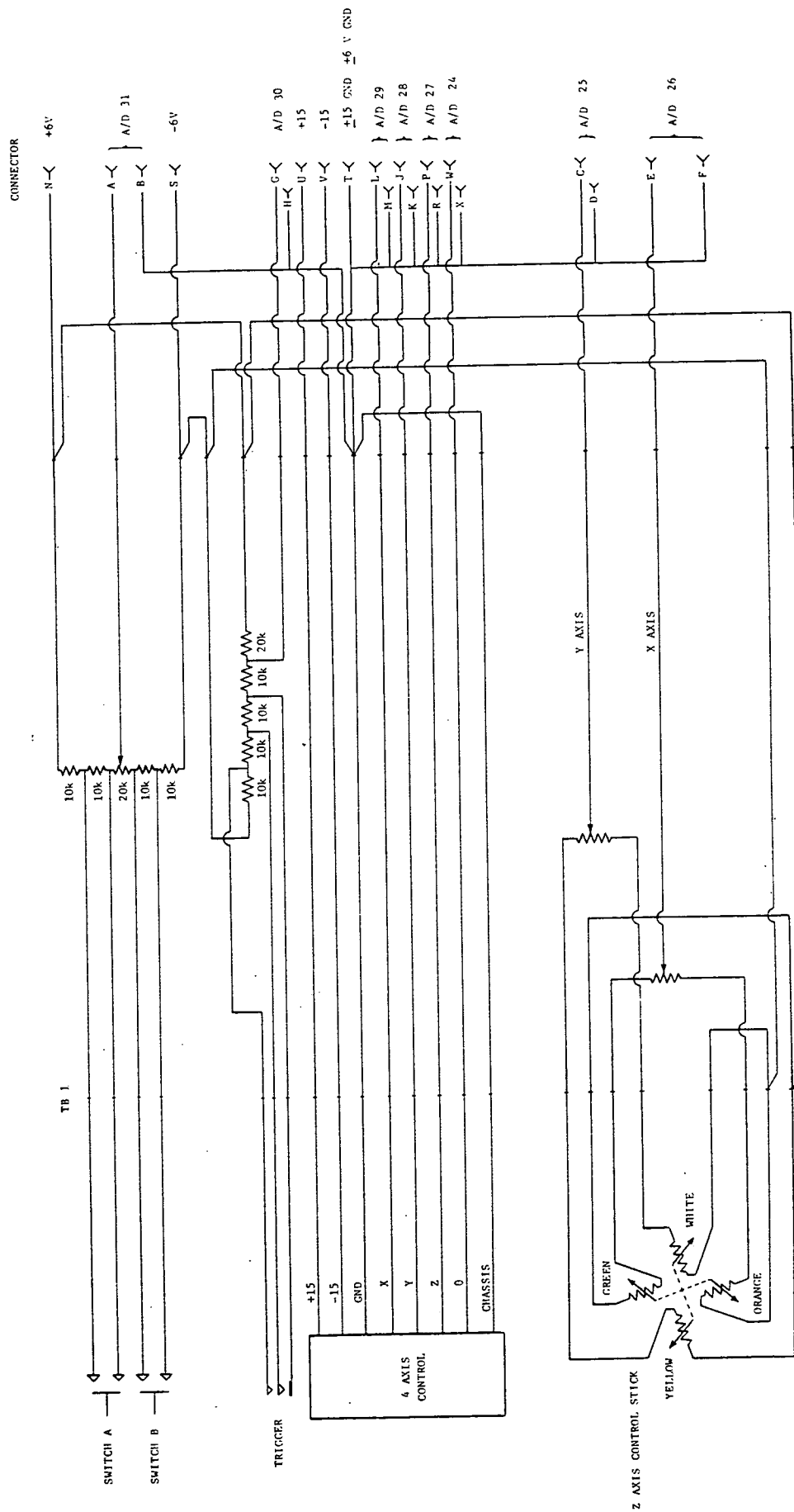


Figure 3-o: MSI 544 Controller Schematic

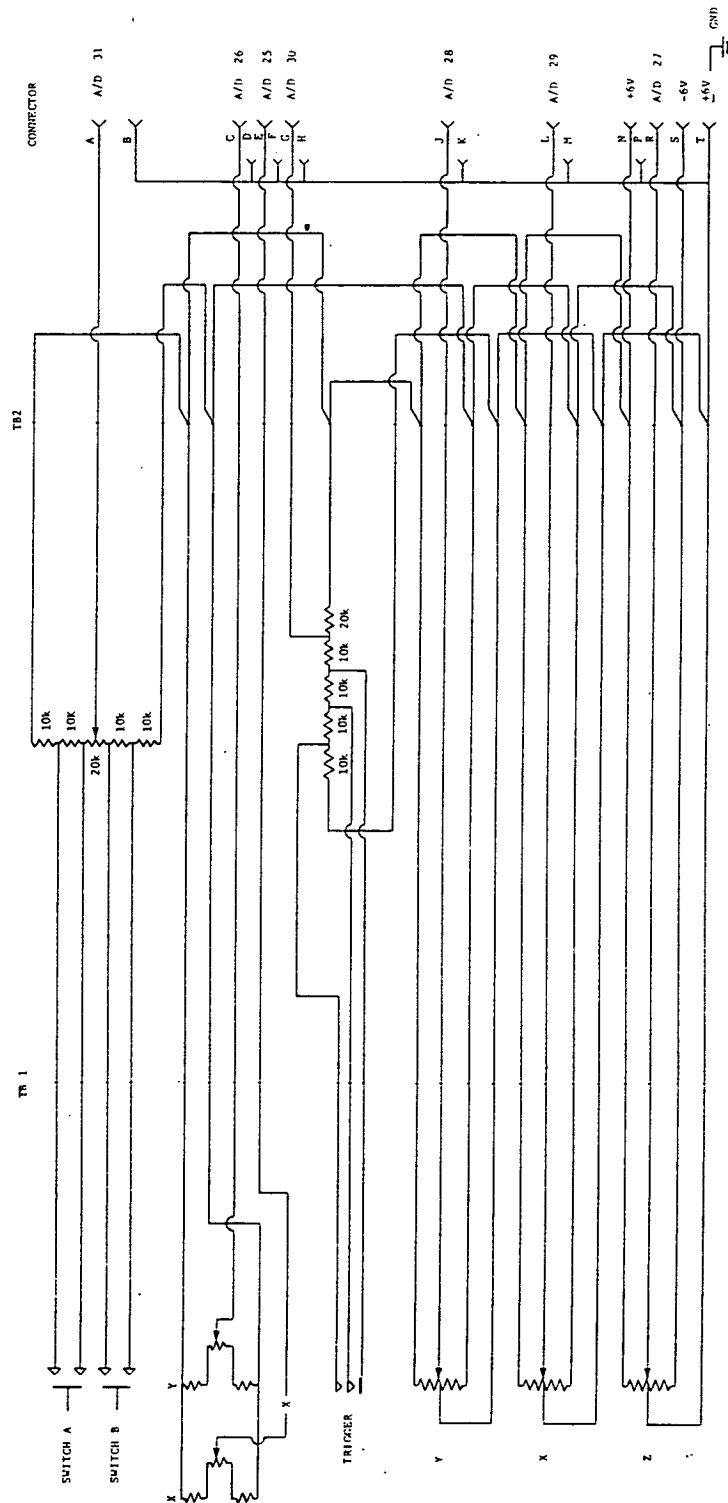


Figure 3-7: MSI 404 Hand Controller Schematic

them directly to the A/D converters. The major axis controls for X, Y, and Z are potentiometer-type controls. These were connected to ± 6 volts, and the wipers were connected to the appropriate A/D converters.

3.2.2.3 Connection of Controllers to A/D Converters

To connect the two controllers via separate A/D converters would have required the use of 15 of the available A/Ds on the SEL 840A. Since the PFMA requires a minimum of 14 converters for the input of rate and position information, as derived from its resolvers, it was necessary to use the same set of A/D converters for both controllers. This was accomplished by installing one Bendix connector on the front of the operator's console. All power supplies and A/D converter inputs to the SEL 840A were then cabled to the rear of this connector. Table 3-2 identifies each connector pin and the device to which it is connected.

Table 3-2: Pin Connector Interface

Bendix Connector Pin Number	Purpose or Device Description	Bendix Connector Pin Number	Purpose or Device Description
A	A/D 31	S	- 6 volt supply
B	A/D 31 ground	T	± 6 volt ground
C	A/D 26	U	+ 15 volt supply
D	A/D 26 ground	V	- 15 volt ground
E	A/D 25	W	A/D 24
F	A/D 25 ground	X	A/D 24 ground
G	A/D 30	Y	A/D 23
H	A/D 30 ground	Z	A/D 23 ground
J	A/D 28	a	+ 18 volts
K	A/D 28 ground	b	- 18 volts
L	A/D 29	c	± 18 volt ground
M	A/D 29 ground	d	unused
N	+ 6 volt supply	e	unused
P	A/D 27 ground	f	unused
R	A/D 27	g	unused

them directly to the A/D converters. The major axis controls for X, Y and Z are potentiometer-type controls. These were connected to ± 6 volts, and the wipers were connected to the appropriate A/D converters.

3.2.4 SEL 840A Computer

The SEL 840A computer (Figure 3-2, above) is a fast, highly versatile, general purpose, 24-bit binary computer which is capable in such areas as:

- General-purpose scientific computation
- Test automation
- Test data collection
- Data logging and display
- Real-time processing.

The SEL 840A computer is used as an interface device between the hand controllers and the manipulator arm. The computer provides the capability of scaling input and output signals for the hand controllers and the arm, so both hand controllers may be made to produce electrically equivalent signals to the arm during a given experiment. It also acts as a controller for the feedback (rate, position, etc.) circuits in the PFMA, so mechanical problems can be overcome without affecting subject performance. During 1978, the operator console for the SEL 840A was replaced by a LSI ADM-3 CRT Terminal, and a new operating system was installed.

The SEL 840A computer also has the capability of allowing inputs from 32 analog devices through A/D converters numbered 0 through 31 and the capability of allowing outputs to 32 analog devices through D/A converters, also numbered 0 through 31.

3.2.5 Hardware Problems

During the course of the contract year, several problems developed with various items of hardware. The problems limited the amount of time that the facility could be effectively utilized.

3.2.5.1 Computer

On several occasions, hardware component failures on the SEL 840A computer caused delays. Some were associated with original SEL equipment. Others pertained to the A/D and D/A converters (originally manufactured by Xerox Corporation), which constitute the direct interface between the computer and the controller(s) and the computer and the manipulator. Essex personnel, along with other contract service personnel, spent a great deal of time and effort isolating and correcting these problems. The total amount of effort spent on these activities was more than 2-1/2 months.

3.2.4.2 PFMA

Several areas of difficulty became apparent with the PFMA during 1978. As mentioned above, the end effector grip force obtainable was measured to be much less than the maximum specified by the manufacturer. The original grip measured was found to be about 89 N (20 lbs). After adjustment to the maximum obtainable with the present electronic interface, the maximum grip force was found to be 134 N (30 lbs). It was determined that this force was adequate for test purposes for the two tests to be undertaken, but could prove to be inadequate for such things as demonstrating Large Space Structure (LSS) assembly. On several occasions, wires broke loose from the connectors between the electronics interface and the PFMA. The cause of this problem was traced to inadequate strain relief provisions on the connectors. To eliminate this problem, it would be necessary to replace most, if not all, of these connectors with other connectors which could be more easily serviced in the event of future problems.

Another problem arose when the PFMA was moved from the previous manipulator room to its present location in the high bay area of Building 4487. The false floor of the new PFMA room is much higher than that in the old manipulator room. This allows the counterweights to strike the floor in certain positions. The problem could be resolved by raising the PFMA arm and its pedestal above the new floor level.

3.2.6 Task Boards

It was determined that with the low jaw grip force available on the PFMA and the manipulator tasks to be evaluated, task boards which would satisfy the testing goals within these operational constraints would be used. The task boards shown in Figures 3-8 through 3-10 were selected for the tasks to be evaluated. The task board in Figure 3-8 was selected for the peg insertion/removal task, and the task board in Figure 3-9 was chosen for the minimum position change task. The task board shown in Figure 3-10 was previously used to demonstrate LSS assembly. However, it remains to be determined whether or not this latter hardware is too heavy for use with the low PFMA jaw grip force.

3.2.7 Proximity Sensors

During the contract period for 1978, the National Bureau of Standards (NBS) delivered proximity sensor hardware to NASA for evaluation. Essex personnel aided in attaching the proximity sensor equipment to the PFMA, debugging the hardware, initial calibration of the sensors, and removal of the hardware from the PFMA after the initial evaluation.

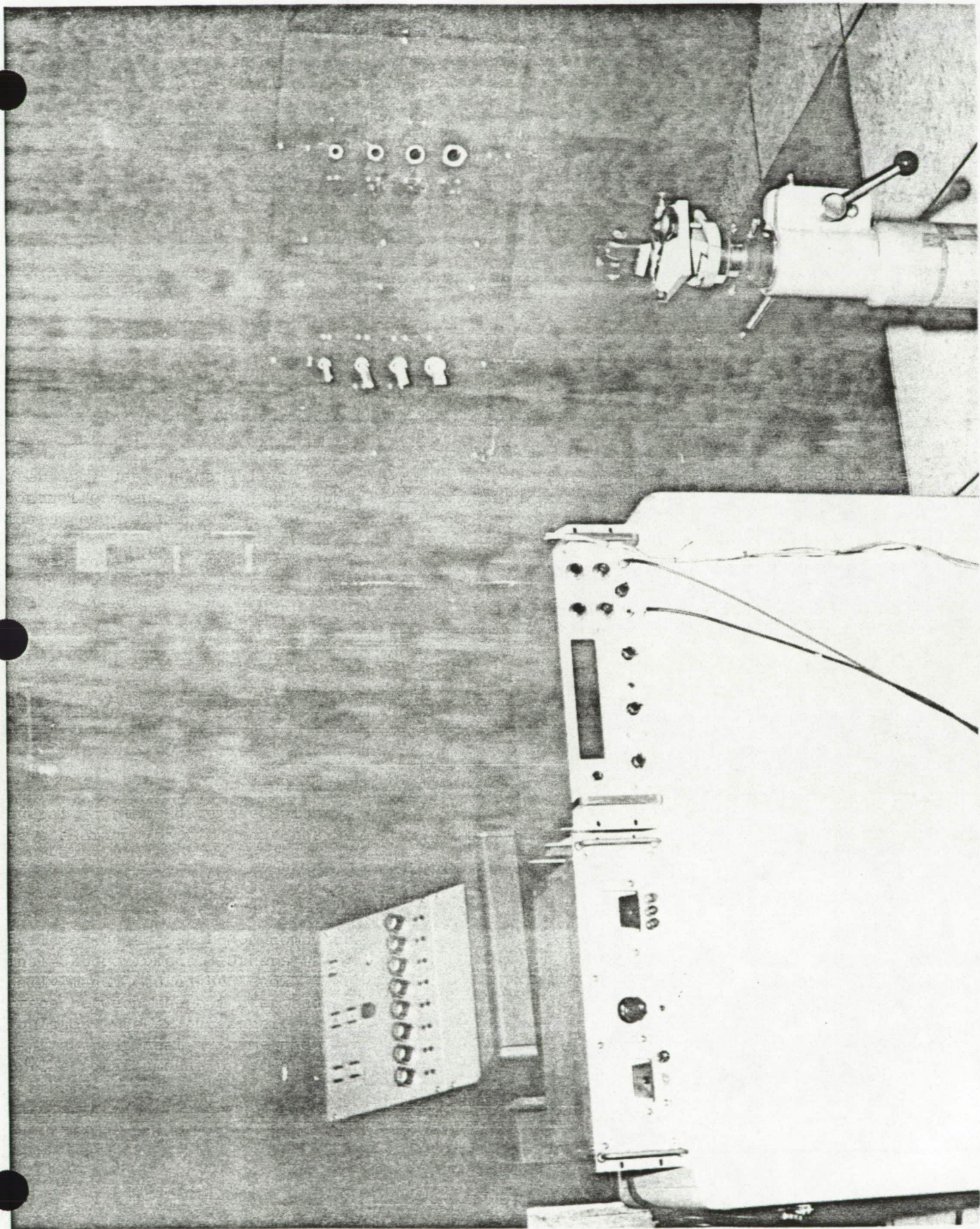


Figure 3-8: Peg Insertion/Removal Task Board and Electronics

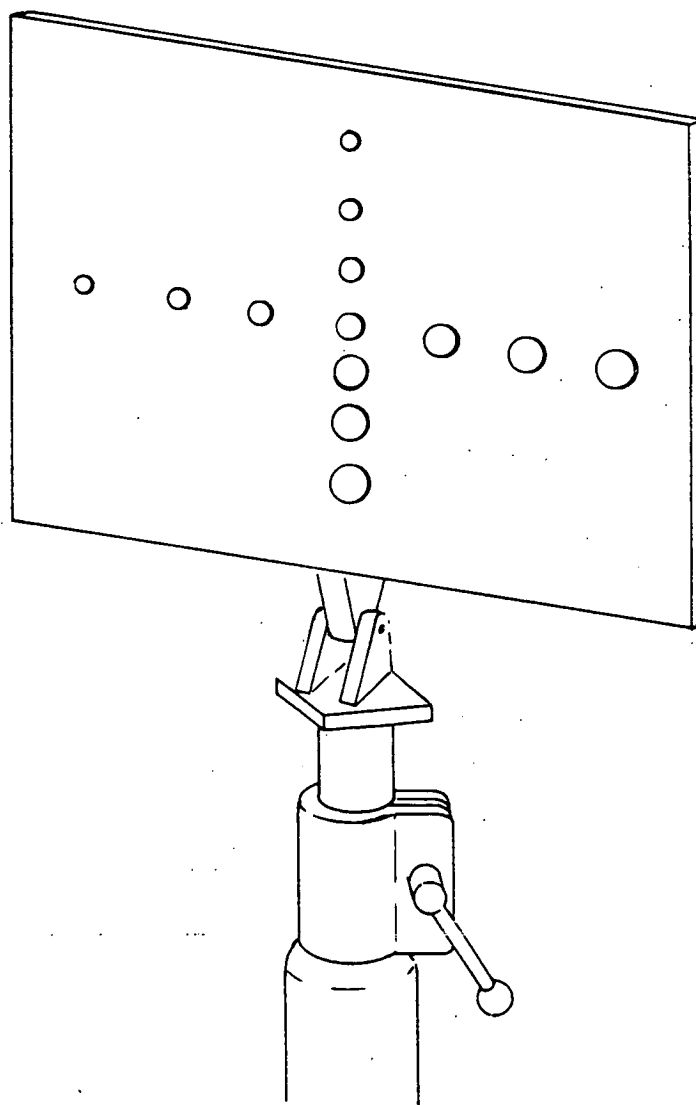


Figure 3-9: Minimum Position Change Task Board

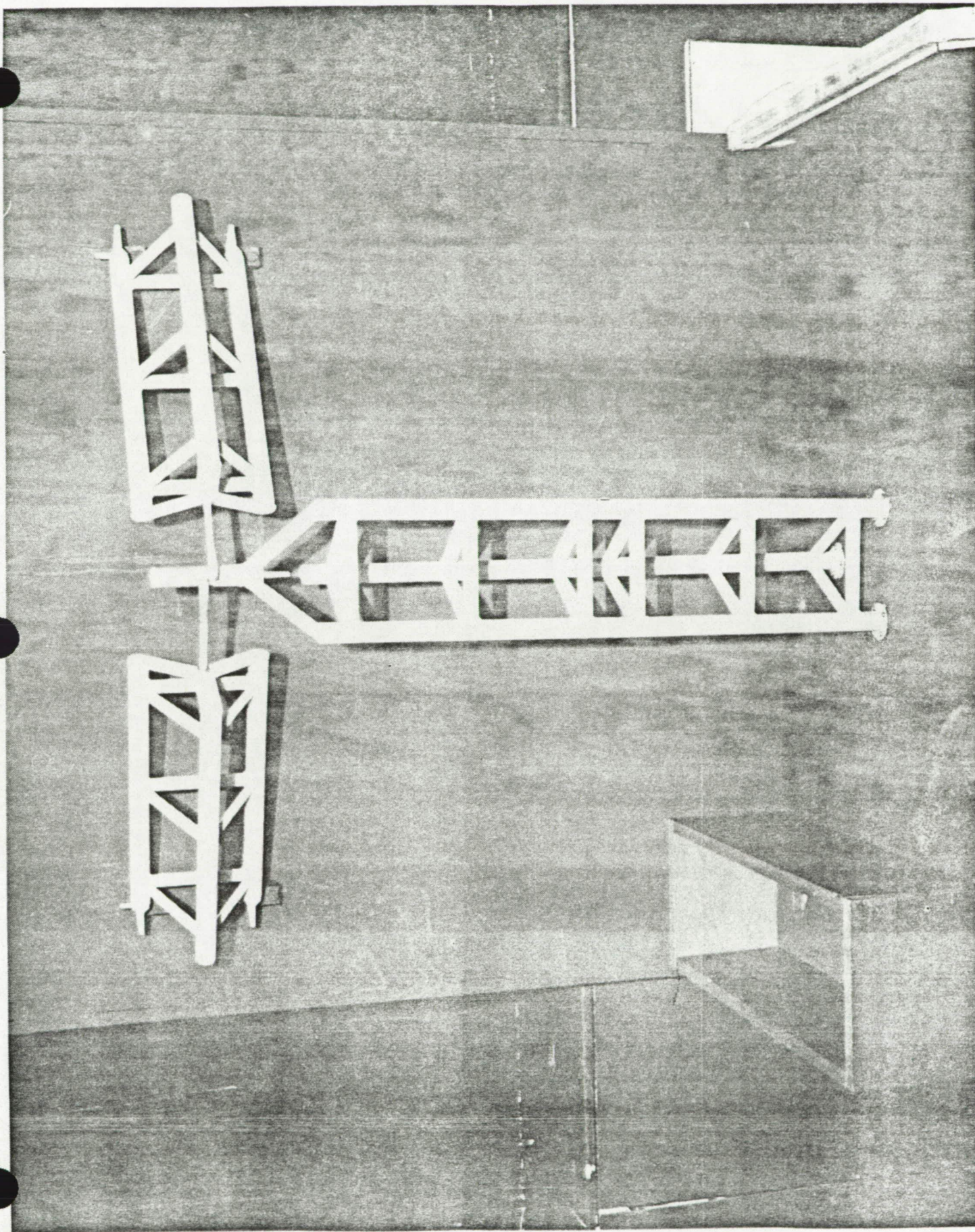


Figure 3-10: Large Space Structure Task Board

The technical specifications for NBS's Proximity Vision System are summarized as follows:

A manipulator wrist-mounted camera with a 35° field of vision (FOV) and a modified, commercially available strobe are mounted such that the camera receives light reflected from objects in the working field. Simple triangulation of the light emitted, light reflected, and camera location then display a line of light (from the strobe), yielding apparent distance on the operator's video monitor. For distances of 0 - 20 cm, an infrared light source mounted in the end effector with its associated sensors is used in conjunction with the strobe. The reflected infrared energy is received by the two photo transistors in the effector tips, and relative distance is graphically displayed on the left and right edges of the operator's video monitor.

3.3 TEST PREPARATION

The research carried on in the manipulator laboratory encompasses studies of manipulator assemblies and test preparation being considered for use on satellite servicing teleoperators and large space structure assembly teleoperators. The teleoperator may be considered a Shuttle payload with a requirement to provide complementary operational support to other Shuttle payloads.

The satellite servicing tasks which the teleoperator may be called upon to perform include:

- Visual inspections
- Removal of modules from a satellite, e.g.,
 - releasing module attachment fasteners
 - breaking line connectors (electrical and fluid)
- Module translation and stowage
- Replacement of module on satellite, e.g.,
 - insertion and locking of attachment fasteners
 - serving as a camera carrier for increased visual documentation of space activities.

The structural assembly tasks the teleoperator may perform include:

- Hardware deployment (from Shuttle or other launch vehicles)
- Assembly of basic structural elements
- Operation of joints
- Attachment of support hardware.

To help assure teleoperator capability to perform these satellite servicing and structural assembly tests, certain research questions were formulated--questions that relate specifically to the controller/manipulator combinations and control laws which have been considered to be possible candidates for flight.

These questions include three principal inquiries into manipulator performance:

- (1) What combination of manipulator/end effector is necessary to perform the satellite servicing structural assembly tasks listed above?
- (2) Which of the two hand controller concepts under consideration can best carry out these tasks?
- (3) Will the previously developed control laws for these hand controller/manipulator/end effector combinations be applicable in their present form, require modification in some way, or prove to be inadequate in any form?

During 1978 the resources available to this effort were expended in several ways. As outlined above, several laboratory tasks were performed. Beyond these, other areas were undertaken as described below.

3.3.1 Software Development/Modification

At the time when the computer facility became available for test preparation, a collection of software existed which had been developed for the Extendible Stiff Arm Manipulator (ESAM), some of which had been debugged and tested. It was determined, however, that modification of this software to operate the PFMA would be a larger undertaking than starting anew, using some of the existing software where possible. Existing algorithms were developed and implemented in computer code to cause the PFMA to operate in a joint-by-joint mode. When this computer code was tested, it was found to enable less than precise control, but it proved workable for analog simulation.

The next step consisted of trying to implement the "hawk" mode of operation. This consisted of computer code using Martin Marietta's control law equations as modified at MSFC by D. R. Scott (EC24). These equations are given in "Control Laws for Hand Controller vs. Manipulator Arms", D. R. Scott, EC21-WP-1-77, April 18, 1977. This paper describes the relationships between the various degrees of freedom of the hand controller(s) and the PFMA as well as giving equations to define the relationships between axes of the PFMA to implement the "hawk" mode and Terminal Device (TD) mode. The "hawk" mode enables the end effector to remain in a given relationship to some fixed plane with any other axes in some form of translation. The TD mode enables the end effector to remain in a given relationship to some fixed point with all other axes in motion.

As it turned out, only partial implementation of the "hawk" mode was possible. There were several reasons for this, the primary one being that position feedback from the PFMA to the computer was not available. During 1978, only rate feedback information was available. By integrating this information, a very gross approximation of the change in position (ΔP) could be obtained for any given joint at any time. A scheme was developed to keep track of position, but it was determined that the bookkeeping for this would

require so much computer overhead that the arm could not perform its tasks in a real-time mode.

The modified "hawk" mode implemented on the SEL 840A uses some of the relationships derived in the Scott paper along with several Essex modifications. A series of scale factors was applied to the various feedback signals to make them usable in the given relationships. In addition, combined shoulder/elbow movement, which is part of the "hawk" mode and the terminal device mode, was included in the modified "hawk" mode. This proved to be necessary for the actual operation of the arm in the selected tasks.

The implementation of the terminal device mode of operation will not be possible without accurate position feedback information. Even then, it may require both rate and position feedback information which, due to hardware limitations, is not currently available.

3.3.2 Test Plans

The test plans were developed for the test and evaluation of operator performance using the PFMA and selected hand controllers. Briefly, the tests are designed to measure operator effectiveness in executing small changes in effector tip position and to evaluate system performance in insertion/extraction tasks. A complete experimental plan for both tasks is included in Appendix A of this report.

3.3.3 Operational Procedures

To ensure the safe operation of the complex system equipment, a set of power up/power down procedures was formulated and disseminated to manipulator personnel. A complete power up/power down listing is documented in Appendix B.

3.4 TEST SUBJECT TRAINING

In the past, test programs have been conducted with various hand controller/manipulator combinations using an existing pool of all male test subjects. This pool formed over a period of years with subjects being right hand/right eye dominant and able to pass both general physical exams as well as visual screening exams conducted by NASA. This pool has consisted of as many as 12 subjects, but due to changes in work assignments and other reasons, many of these individuals were no longer available during the current contract period.

To supplement the existing subject pool and to obtain a better sample of individuals, it was decided to include several qualified persons at NASA. Qualifications included physical fitness and a technical background, i.e., engineer, physicist, mathematician, etc.

Several new test subjects were acquired and training was begun for most of these subjects during the year. Training consisted of allowing the test subjects to operate the PFMA with the MSI-404 hand controller. Subjects were instructed to touch a series of dots with the end effector in either a horizontal or vertical plane (Figure 3-11). Due to the problems with the

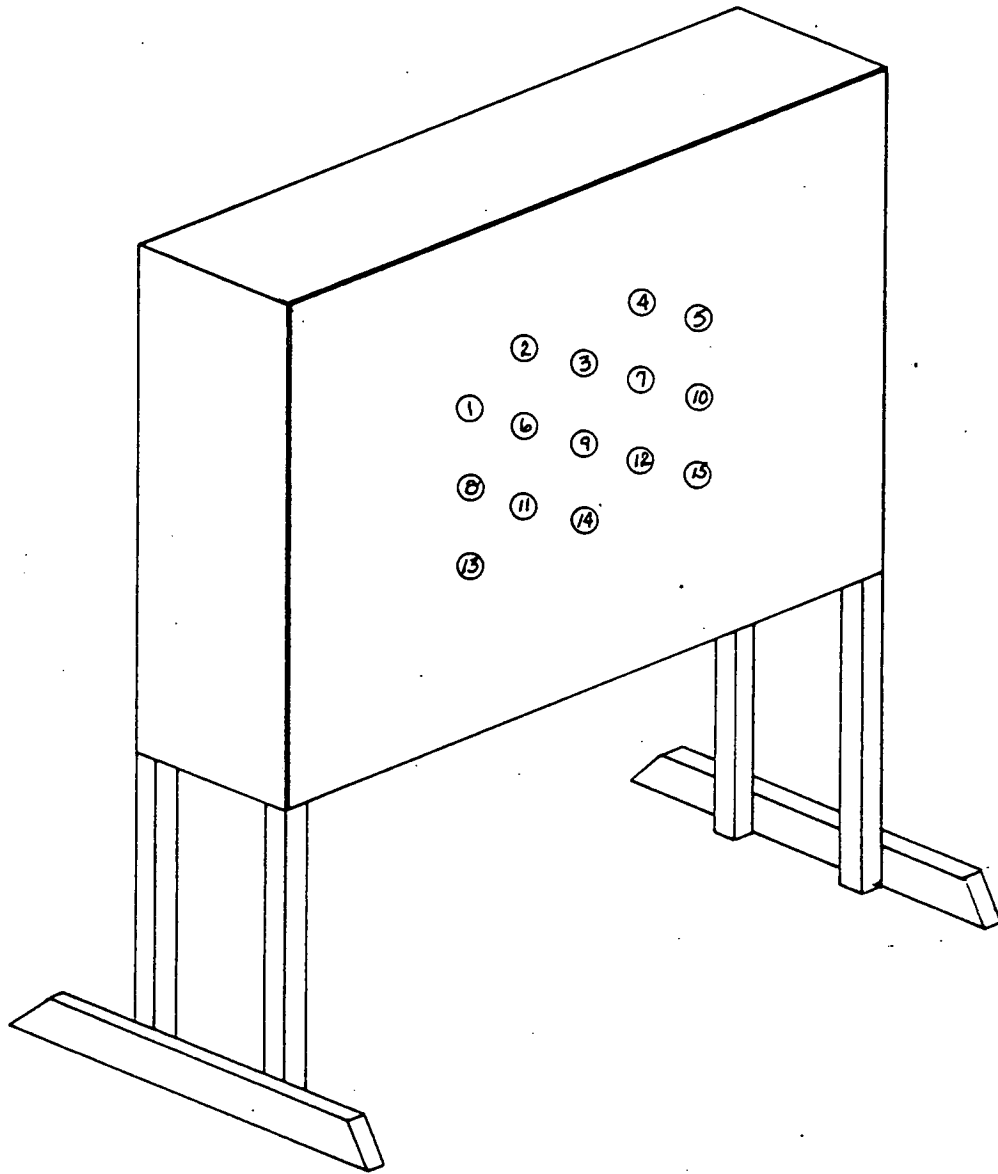


Figure 3-11: Training Task Board

computer hardware, only a limited amount of training was accomplished. To date, five new subjects have had actual hands-on experience with the controller/manipulator combination for a total of more than six hours. Experienced subjects have also had time on the hardware. At present, three experienced subjects have spent over three hours using the hardware.

3.5 RESEARCH STATUS

This section describes the current status of research in the Manipulator Laboratory and outlines the activities Essex feels are needed to continue this research. The accomplishments in the hand controller/manipulator evaluations for the current year included:

- Successful interfacing of the MSI-544 and the MSI-404 hand controllers with the PFMA manipulator
- Determination that the MIT SD-2 hand controller could not be used successfully with the PFMA
- Completion of coding, debugging, testing and calibration of the software for controlling the PFMA with the selected hand controllers
- Selection of the DOF of the hand controller corresponding to a particular DOF of the PFMA (the original proposal given in the document by Don Scott, EC24, cited above, has been modified so that the same DOF in both controllers yield the same movement in the PFMA)
- Selection of criteria for additional test subjects to be used in the evaluation program
- Acquisition of additional test subjects using above criteria
- Completion of test plans for initial evaluation of controller/manipulator combinations
- Initial familiarization and training of test subjects on actual hardware
- Completion of procedures document for power up/power down of the PFMA/computer and its related hardware
- Moving the PFMA and related hardware to a new location in a high bay area.

Using the Essex "hawk" mode of operation for the controller/manipulator combinations available, prospective test subjects are currently undergoing training and screening in the use of the hardware using a simulated task board (Figure 3-11). Once this process has been completed and the primary and backup test subjects have been selected, testing should begin using the

peg insertion/removal task. While this test is underway, construction of the minimum position change task board will be undertaken, following which testing should proceed using this task board. During this same period of time, the LSS task board will be modified to enable testing to be done with this hardware. A test plan should be generated for this test prior to initiation of testing.

Once the required modifications to the PFMA have been completed by NASA, i.e., when the hardware is installed so that position encoded information is available as a feedback to the computer for processing, the various tests should be repeated using position feedback information. In addition, other hand controller concepts should be interfaced to the PFMA for further testing, as required. Work should also include use of the NASA control laws where applicable.

The data collected from these tests may then be used to evaluate the two (or more) controllers and to support the selection and/or design of the controller to be flown with the PFMA. This evaluation should cover the following parameters:

- One-hand vs two-hand approach
- Degrees-of-freedom per hand
- Degrees-of-freedom operable simultaneously
- Force output vs displacement output
- Controller configuration
- Correspondence between manipulator action and controller action
- Rates and gains
- Deadband.

Once these parameters have been addressed and some answers to the questions posed have been obtained, new avenues of study should present themselves.

It appears that the current end effector on the PFMA is adequate for the testing program in progress. However, an entirely different jaw design may be needed for a flight PFMA. In many attempts to manipulate standard off-the-shelf equipment, such as connectors, switches, handles, etc., the jaw was unable to successfully manipulate the items. Tradeoffs will have to be made to determine if it is more reasonable to modify the PFMA end effector or to develop special hardware to interface with the PFMA.

From simulation experience, it appears that special hardware (i.e., specially designed handles, valves, connectors and switches) will be required to perform actual satellite servicing tasks because of the PFMA's present inability to manipulate most off-the-shelf hardware.

In summary, it appears that the PFMA can be an extremely useful tool for on-orbit satellite servicing and structure assembly pending the development of the control law software and compatible connectors, switches, doors, etc. Additional research in the manipulator laboratory will support the development of the PFMA to a working flight demonstration unit.

4.0 EXECUTIVE SUMMARY

This section provides a brief overview of the technical accomplishments made by Essex Corporation during 1978. The details of the technical effort for mobility systems appear in Section 2.0 of this report, and those for manipulator systems appear in Section 3.0.

4.1 MOBILITY SYSTEM EVALUATION LABORATORY

During 1978, two classes of tests were conducted in the Mobility System Evaluation Laboratory: operational simulations and system engineering surveys. The purpose for the operational simulations was to test specific subsystem configurations on maneuvering and docking tasks, while the purpose of the engineering surveys was to determine empirically the test facility's operating parameters.

4.1.1 Engineering Survey to Measure Mobility Unit Pitch and Yaw Acceleration

Technical data on the MU were collected which describe the pitch and yaw acceleration values in the constant thrust mode of operation.

The test for yaw acceleration levels involved measuring elapsed time to complete a 360° rotation about the center air bearing. The results show that the MU made a 360° yaw maneuver in an average 15.7 seconds, terminating in a mean acceleration of 3.25×10^{-3} radians/sec² (.19°/sec²).

The test for pitch acceleration involved measuring elapsed time to pitch down from 0° to -17.5° (pitch down limit). The results were: 4.35 sec to complete pitch maneuver, ending in a terminal acceleration of 7.44×10^{-3} radians/sec² (.45°/sec²).

It was noted for planning purposes that time and acceleration measures yield smaller variances if the MU is "exercised" prior to collection of data. The exercises will be part of the system warm-up and calibration runs during future testing.

4.1.2 Engineering Survey to Measure Mobility Unit Thruster Impulse in the Constant Thrust Mode

Technical data were collected to calculate thruster impulse as a function of acceleration and MU displacement over time. These data were then compared to thruster bench calibration figures.

The results indicate that forward impulse for each of two thrusters be defined as within a range of 4.45 to 6.45 N-S. The two thrusters drive the MU forward approximately 30 ft over 28.9 sec yielding a total thruster pair impulse of between 8.9 to 12.9 N-S. Utilizing mean data, each thruster can be

described as imparting 5.5 N-S thrust impulse.

4.1.3 Engineering Survey to Measure Mobility Unit Fuel Consumption as a Function of Thrust Mode

Three thrust modes--constant, trained pulse, and single pulse--were exercised over a given period of time and the pressure (fuel) drop was recorded. For the single pulse mode, data are given in signals commanded over time (mean command length of one signal/.33 S).

Table 4-1: Fuel Consumption Summary

Thruster Mode	Mean Fuel Consumption Rate (ΔP)	Mean Flow Rate (Mass/Second)
Constant	$9.58 \times 10^3 \text{ N/m}^2/\text{S}$ (13.9 psi/S)	0.086 kg/S (0.189 lb m/S)
Trained Pulse	$79.3 \times 10^3 \text{ N/m}^2/\text{S}$ (11.5 psi/S)	0.0706 kg/S (0.156 lb m/S)
Single Pulse	$14.82 \times 10^3 \text{ N/m}^2/\text{cs}^*$ (2.15 psi/cs*)	0.0133 kg/cs* (.02924 lb m/cs*)

*cs = command signal

4.1.4 Engineering Survey to Determine Mass Loading of the Mobility Unit

The upper bay of the MU is supported by a cylindrical air bearing which permits rotation and pitch about a control axis. The requirement to mass load the air bearing for support of full scale mockups was addressed in this survey. At 40 psi, the MU was loaded with a balanced additional weight of 143 kg (316 lbs).

The results showed an increase in air bearing pressure to 55 psi, which still permitted a friction-free surface at the central air bearing. The evenly balanced load permitted motion about the central axis, indicating that full scale mockups on the order of 544 kg (1200 lbs) could be used on the upper bay of the Mobility Unit for simulations and tests.

4.1.5 Engineering Survey to Evaluate Resurfacing Epoxy Floor

The present air bearing floor has developed some surface anomalies due to thermal properties of the subfloor. In preparation for resurfacing the

air bearing floor, it was necessary to mix appropriate samples of the resin and hardener and to test these for hardness, uniformity, and color.

Twenty-four samples were prepared with the mix and batch numbers recorded for later reference. The samples were cured at 73°F for 72 hours and then examined for a smooth, bubble-free surface and internal integrity. The results indicate that utilizing the mix and batch data from this study, a uniform, hard, smooth surface can be expected during resurfacing of the floor.

4.1.6 Operational Evaluation of a Two-Hand Controller Concept Using the Mobility Unit

Rendezvous and docking maneuvers were performed using the MU controlled by a pair of joystick controllers. The data were then compared to previously acquired information on rendezvous and docking which utilized a single stick, integrated controller. Two thrust modes--trained pulse and constant thrust--were used to dock with two classes of satellites, one with less mass than the MU, and the other simulating more mass than the MU. The results are summarized in Table 4-2.

Table 4-2: Time and Fuel Expended in Docking MU
with Two Classes of Satellites Under Two
Conditions of Thrust, Single- vs Two-Hand
Controller

	Single Integrated Controller				Two-Hand Controller			
	Target Small Mass		Target Large Mass		Target Small Mass		Target Large Mass	
	CT	TP	CT	TP	CT	TP	CT	TP
Elapsed Time To Dock (sec)	324	183	103	160	207	191	135	142
Fuel Expended In Docking (kg)	292	130	162	128	270	167	187	128

where CT = Constant Thrust,
TP = Trained Pulse

4.1.7 Operational Evaluation of a Two-Hand Controller Concept Using the Docking Retrieval Mechanism

A second comparison of single and dual hand controllers was made using a Docking Retrieval Mechanism, which is a device designed to capture "prepared" satellites. The results of these tests are shown in Table 4-3, including the time and fuel expended for the two classes of controllers, for the two thrust modes employed, and for the two extensions of the DRM--fully extended and fully retracted.

Table 4-3: Time and Fuel Expended in Docking the DRM with a Satellite in an Extended or Retracted Configuration Under Two Conditions of Thrust, Single- vs Two-Hand Controller

	Single Integrated Controller				Two-Hand Controller			
	DRM Extended		DRM Retracted		DRM Extended		DRM Retracted	
	CT	TP	CT	TP	CT	TP	CT	TP
Elapsed Time To Dock (sec)	63	82	92	87	109	116	129	132
Fuel Expended In Docking (kg)	65	45	68	57	68	51	85	68

where CT = Constant Thrust,
TP = Trained Pulse

4.1.8 Operational Evaluation of a Solar Maximum Mission Docking Simulation

A docking simulation with a low fidelity mockup of the Solar Maximum Mission payload was conducted to measure the effects of docking target configuration on an operator's capability to perform rendezvous, alignment and docking tasks.

Using one of two MU onboard cameras, operators approached and docked with the SMM mockup, which was outfitted with two docking targets aligned with one or the other camera. One camera/target pair was CG mounted, with the camera mounted inside the docking drogue. The other camera/target pair was mounted off the center approach axis.

The docking performance for each camera/target configuration was measured in terms of fuel and time expended. Using the center mounted (drogue) camera/target pair, the operator expended just less than 90 sec and 37 kg of fuel. Using the top mounted camera, the operator required 94 sec and 38.5 kg of fuel. The only finding of significance was the effect of camera/target on fuel consumption.

4.2 MANIPULATOR SYSTEM EVALUATION LABORATORY

During the testing year, the major activity was moving and re-establishing the laboratory and its support equipment. Essex participated in this activity and also made preparations for the test program in the new facility.

4.2.1 Operational Procedures

With the establishment of the new facility, it became increasingly apparent that a formal power up and power down procedure needed to be developed and maintained with the equipment. This was accomplished and documented. The procedures appear in Appendix B of this report.

4.2.2 Test Subject Training

A concerted effort was made to identify qualified and willing subjects to augment the existing subject pool. To bring the new subjects' behavior up to par with that of the trained subjects already in the program, a manipulator training program was initiated. Subjects were permitted to familiarize themselves with the arm and controller, and then they were directed through a series of exercises from which baseline operator performance data will be derived.

4.2.3 Test Plans

Current test plans for a minimum position change test and a probe insert/extract test were formulated and approved for implementation during the testing program. These plans appear as Appendix A of this report.

4.2.4 Software Development/Modification

Appendix C of this report is the program listing for the manipulator system software modifications necessary to control the manipulator in a joint-by-joint mode and in a partial "hawk" terminal pointer mode. Modifications were necessary for the proper operation of the PFMA.

5.0 REFERENCES

1. Earth Orbital Teleoperator Systems and Concepts Analysis--Docking Retrieval Mechanism. Final Report, MCR-76-17, Volume V (Contract NAS8-31290), Martin Marietta Corporation, Denver, Colorado, May 1976.
2. Free-Flying Teleoperator Breadboard Vehicle, S&E-ASTR-6-WP-7-73, July 1973.
3. R. G. Brye, D. E. Henderson, E. C. Pruett, P. H. Slaughter, N. L. Shields, Jr., and M. Kirkpatrick. Earth Orbital Teleoperator Systems Evaluation, Essex Report No. H-78-1 (Contract NAS8-31848). Essex Corporation, Huntsville, Alabama, January 1978.

Appendix A
Test Plans and Experiment Design

MANIPULATOR SYSTEM PERFORMANCE EVALUATIONS

OBJECTIVE: TO MEASURE HUMAN OPERATOR PERFORMANCE USING REMOTE MANIPULATOR SYSTEMS IN EXECUTING SMALL CHANGES IN EFFECTOR TIP POSITION

APPARATUS AND PROCEDURE

A 30.5 cm by 30.5 cm task module with 16 instrumented targets will be employed as the task site. Figure 1 shows the design details of this minimum position change task.

The task module will be securely attached to a heavy duty tripod to permit control of the task module's orientation with respect to the horizontal plane of the manipulator system shoulder. The manipulator system employed will be the Proto Flight manipulator (PFMA) with (1) a joystick rate controller, and (2) a joystick position controller. Visual feedback of the task site will be provided by a Telemation camera system and studio lighting system.

The subject will be seated at the operator's control console which is equipped with televised feedback of the task site, a manipulator controller for commanding the PFMA, and an appropriately arranged work station. A set of standard task instructions will be read to the subject detailing the task and performance parameters, and if these are clearly understood, the experimenter will proceed with performance testing.

The subject's task will be to move the PFMA from a fixed "starting position" to the central disc on the task board and from this central target disc to one of 16 target discs--the particular disc being identified by the test conductor. The central disc and all target discs will be fabricated from electrically conductive material and the contact of the PFMA end effector with a disc will close a circuit and start or stop a time recorder. As can be noted from Figure 1, the target discs are arranged in a cruciform pattern with four different contact diameters (tolerances) and four different movement amplitudes from the center contact. The several tolerances and amplitudes of the task board are being used in conjunction with Fitts' index of difficulty of a movement as a relative figure of merit. Fitts' Law, $ID = \log_2 \frac{2A}{W}$, is derived from information processing theory and has been validated on hand motion/time data, and to some extent on Manipulator Systems (Kirkpatrick, et. al., 1975).

The time from contact with the center disc to contact with the target disc will be recorded, as will any intermediate contact errors. Time to perform the task and task errors will be employed as the dependent measures in this study.

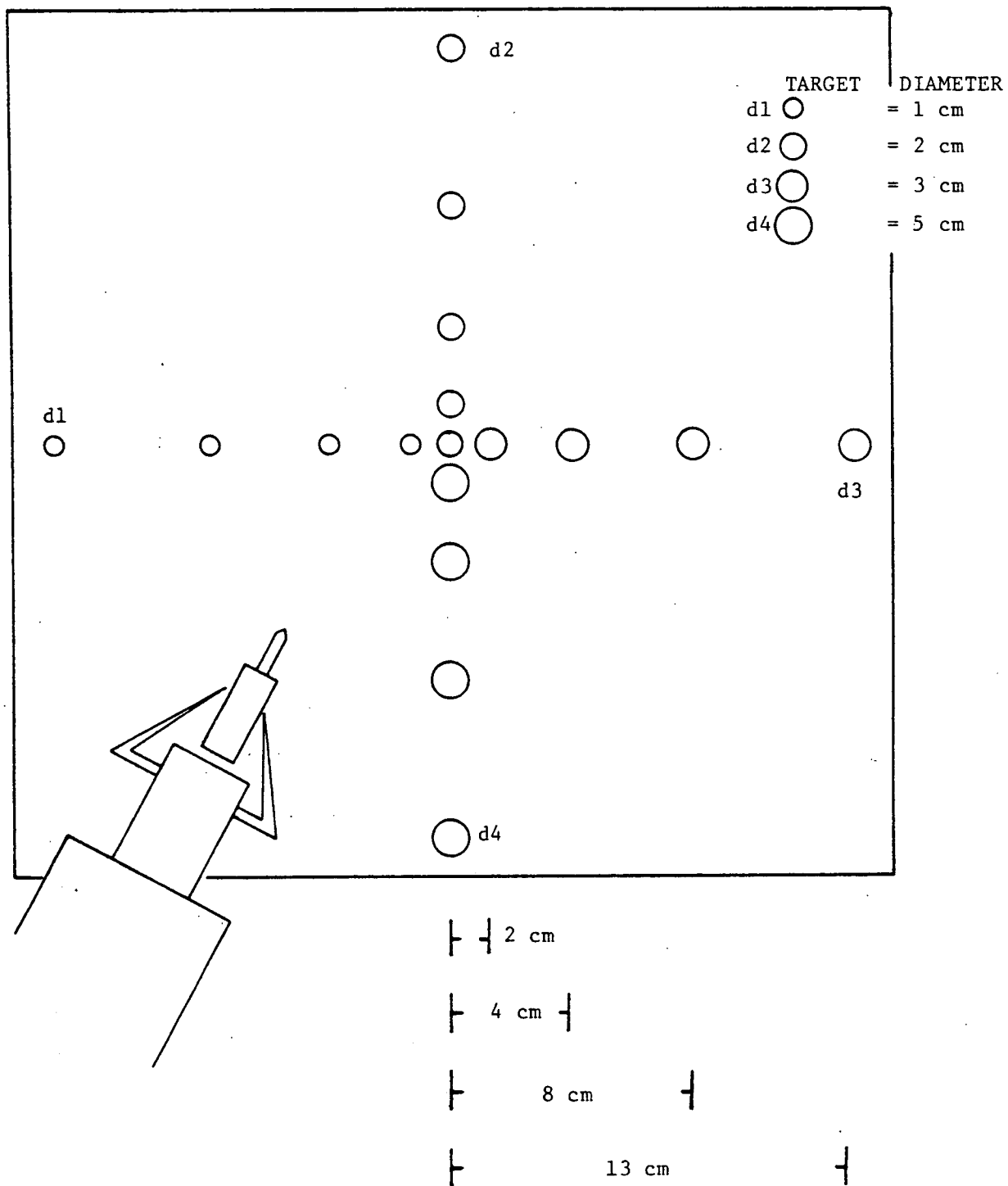
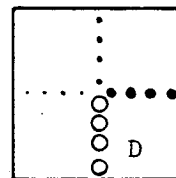
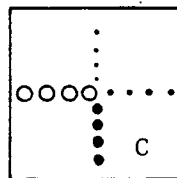
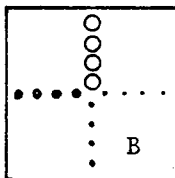
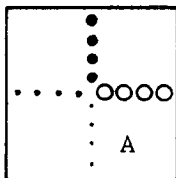


Figure 1 - Minimum Position Change Task Module

EXPERIMENTAL DESIGN

Independent Variables

- o Four target distances from the center disc
 - 2 cm from 0
 - 4 cm from 0
 - 8 cm from 0
 - 13 cm from 0.
- o Four target tolerances
 - 1 cm diameter
 - 2 cm diameter
 - 3 cm diameter
 - 5 cm diameter.
- o Four orientations of the task board



- o Two controller designs
 - rate controller
 - position controller.

Dependent Variables

- o Response latency
- o Response errors.

Control Variables

- o Orientation of the task board with respect to the nominal PFMA rest position
 - in plane and perpendicular to the end effector
- o Video/target/PFMA geometry
 - Fixed to reflect the operational configuration
- o Lighting at the task site.

The subjects will each undergo a series of training trials such that the subject's performance moving the arm from left to right and right to left approaches asymptote, as is the performance moving the end effector in and out.

Blocks of ten training trials at each movement will be run until performance does not vary +5% over the ten trial block. Training will not require a replication of the task requirements.

Four subjects will be utilized in this experiment in a treatment by subjects design with the order of presentation as follows:

S ₁	S ₂	S ₃	S ₄
<u>X</u>	<u>X</u>	<u>Y</u>	<u>Y</u>
O ₁	O ₂	O ₃	O ₄
O ₄	O ₃	O ₂	O ₁
O ₂	O ₄	O ₁	O ₃
O ₃	O ₁	O ₄	O ₂
<u>Y</u>	<u>Y</u>	<u>X</u>	<u>X</u>
O ₄	O ₃	O ₂	O ₁
O ₂	O ₁	O ₄	O ₃
O ₁	O ₄	O ₃	O ₂
O ₃	O ₂	O ₁	O ₄

S = Subjects
 X = Rate Control
 Y = Position Control
 O = Orientation of the Board
 D = Distance
 T = Tolerance } Random Assignments

This yields a subtotal of 128 combinations for each of four subjects who will complete two replications of each combination for a total of 256 trials during this test. The data will be subjected to an analysis of variance to derive main effects and interactions of interest. The F ratio will be used to test for statistical significance.

Kirkpatrick, M., Shields, N.L., Jr., Malone, T.B., Brye, R.G. and Frederick, P.N., Manipulator System Performance Measurements, Mechanism and Machine Theory, 1972, 12.

July 31, 1978

MANIPULATOR SYSTEM PERFORMANCE EVALUATIONS

OBJECTIVE: TO MEASURE HUMAN OPERATOR PERFORMANCE USING REMOTE MANIPULATOR SYSTEMS IN EXTRACTION, INSERTION TASKS

APPARATUS AND PROCEDURE

A 30.5 cm by 61 cm task module of black phenolic will be the principal task site. The module (Figure 1) will be drilled with four pairs of holes, these being 9.5, 12.7, 15.9 and 19.1 mm, and these holes will be equipped with electric sensors behind the task module. The sensors will serve to record the presence (absence) of a peg in a hole. The pegs (Figure 2) are 7.9, 11.1, 14.3 and 17.5 mm in diameter and are designed to fit within their holes with 1.6 mm clearance.

The task module will be securely attached to a heavy duty tripod to permit control of the task module's orientation with respect to the horizontal plane of the manipulator system shoulder. The manipulator system employed will be the Proto Flight manipulator with (1) a joystick rate controller, and (2) a joystick position controller. Visual feedback of the task site will be provided by a telemetry camera system and studio lighting system.

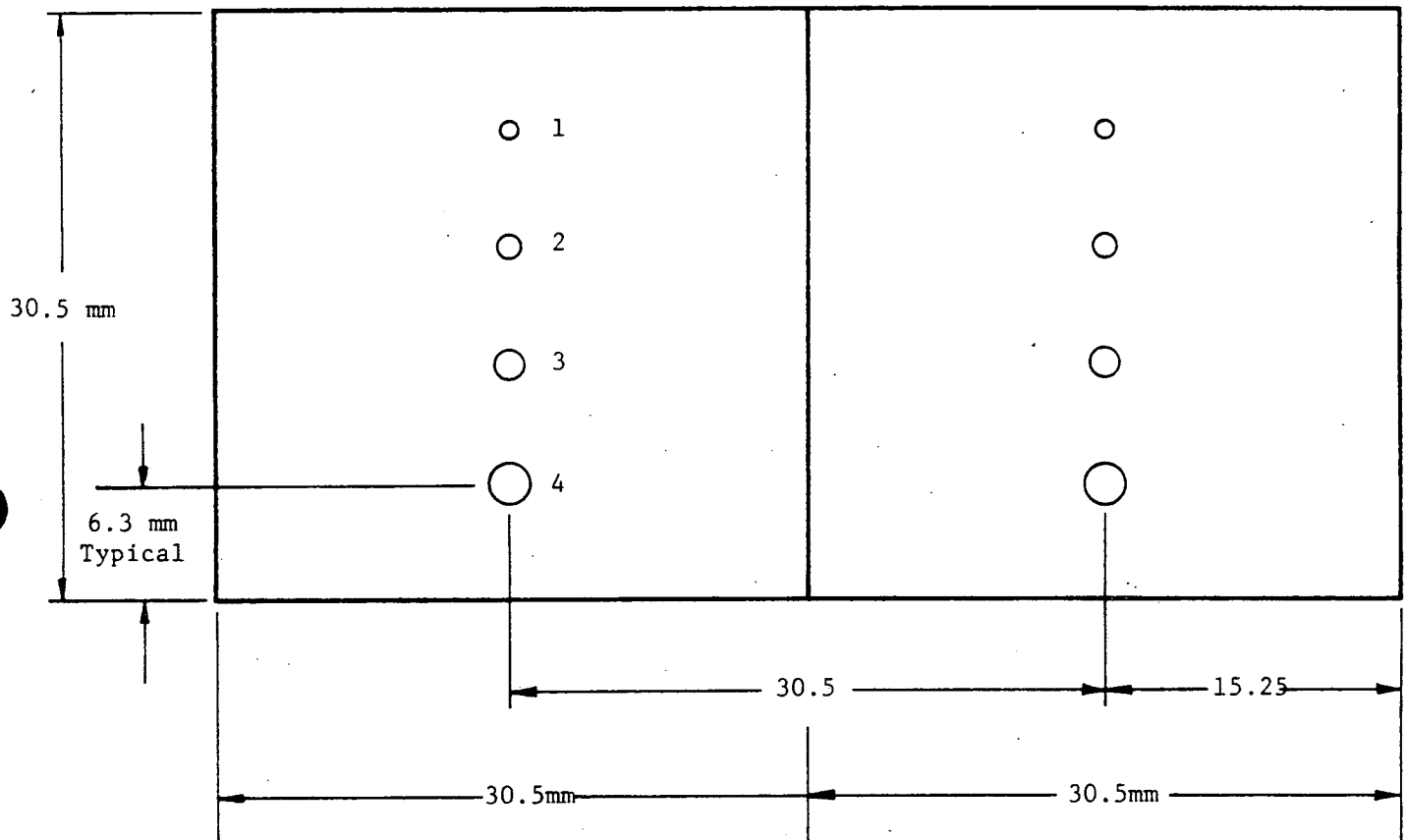
The subject will be seated at the operator's control console which is equipped with televised feedback of the task site, a manipulator controller for commanding the PFMA, and an appropriately arranged work station. A set of standard task instructions will be read to the subject detailing the task and performance parameters, and if these are clearly understood, the experimenter will proceed with performance testing. The subject's task will be to move the PFMA end effector to a designated peg and extract it from its hole, then move it to its paired hole on either the right or left side of the task module, inserting it far enough to close the electrical contact at the back of the hole.

The time from the removal of a peg from one hole to its insertion in its paired hole will be automatically recorded by an off line clock. The subject will then be given the next instruction and proceed through the test trials at the direction of the experimenter. The recorded time will be the dependent measure of interest, although errors in peg selection or insertion errors will also be recorded. The errors in peg selection bear more on human operator perception than on system characteristics and will be considered secondarily.

EXPERIMENTAL DESIGN

Independent Variables

- o Four peg and hole pair sizes
 - 7.9 and 9.5 mm
 - 11.1 and 12.7 mm
 - 14.3 and 15.9 mm
 - 17.5 and 19.1 mm



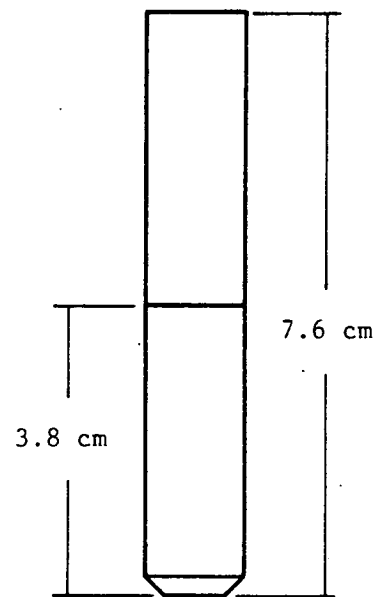
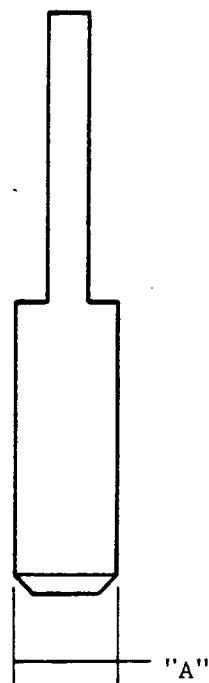
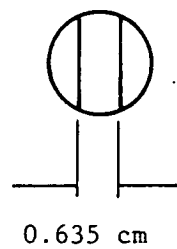
Peg Hole

Corresponding Pegs

- 1 = ○ = 9.5 mm
 2 = ○ = 12.7 mm
 3 = ○ = 15.9 mm
 4 = ○ = 19.1 mm

- 7.9 mm
 11.1 mm
 14.3 mm
 17.5 mm

Figure 1 - Insertion/Extraction Dexterity Module



"A": Peg 1 = 7.9 mm
Peg 2 = 11.1 mm
Peg 3 = 14.3 mm
Peg 4 = 17.5 mm

Figure 2 - Insertion/Extraction Dexterity Test Pegs

- o Two directions of placement
 - left to right
 - right to left
- o Three orientations of the task board
 - normal to the PFMA extension axis
 - pitched up 10° from normal
 - yawed toward the camera 10°
- o Two controller designs
 - rate controller
 - position controller.

DEPENDENT VARIABLES

- o Time to remove, transfer and replace a designated peg
- o Placement errors.

CONTROL VARIABLES

- o Camera locations and geometry
- o Lighting at the task site
- o PFMA configuration
- o Order of presentation
- o Clearance of peg and hole.

The subjects will each undergo a series of training trials such that the subject's performance moving the arm from left to right and right to left is asymptotic as is the performance moving the end effector in and out. Blocks of ten trials at each movement will be run until performance does not vary $\pm 5\%$ over the ten trial block. Training will not require a replication of the task requirements:

Six subjects will be utilized in this experiment in a treatment by subjects design with the order of presentation as follows:

S ₁	S ₂	S ₃	S ₄	S ₅	S ₆
X ₁	X ₂	X ₃	Y ₁	Y ₂	Y ₃
X ₂	X ₃	X ₁	Y ₂	Y ₃	Y ₁
X ₃	X ₁	X ₂	Y ₃	Y ₁	Y ₂
Y ₃	Y ₁	Y ₂	X ₃	X ₁	X ₂
Y ₂	Y ₃	Y ₁	X ₂	X ₃	X ₁
Y ₁	Y ₂	Y ₃	X ₁	X ₂	X ₃

S = Subjects

X = Rate Control

Y = Position Control

1 = Normal orientation with respect to PFMA

2 = 10° offset toward camera

3 = 10° pitch up.

This yields a subtotal of 48 combinations for each of six subjects who will complete three replications of each combination for a total of 144 trials per subject. The data will be subjected to an analysis of variance to derive main effects and interactions of interest. The F ratio will be computed as the test of statistical significance.

It is projected that 158 hours of testing will be required for data collection with each subject being limited to two hour testing sessions to avoid fatigue. Each subject will participate for approximately 20 hours of tests.

Appendix B

Protoflight Manipulator Standard Operating Procedures

PROTOFLIGHT MANIPULATOR PROCEDURES - POWER UP

RM 234

STEP 1.

In the PFMA CONTROL ROOM, check the status of the following controls (See Figure 1 for locations):

"CONSOLE"	- OFF (down)
"STAND 1"	- OFF (down)
"28 Vdc"	- OFF (black)
"DISCRETES 1-10"	- OFF (down)

RM 236

STEP 2.

In the SEL COMPUTER ROOM, check to see that the computer power is ON. POWER ON is the responsibility of SEL personnel and Essex will NOT bring the computer up.

Essex will check that the computer is up prior to any other activation step.

When power is on, the SEL will display the following:

- o CRT/KB = Willies Weakly Workout (W³)
- o Panel Switches 11, 12, 17, 19, 21 will be in the UP position (one or more of these)
- o To Input Program at the SEL Panel:
 - a. All Switches (11, 12, 17, 19, 21) = OFF
 - b. Switch 23 = ON
 - c. Wait until W³ program terminates and CRT displays = 0 TOTAL ERRORS
 - d. Type in
 - CP PHIL RETURN
 - EX RETURN
 - PC RETURN
 - e. Verify PFMA cables are connected to the SEL. The two cables for the PFMA are labeled "PFMA INPUT" and "PFMA OUTPUT."

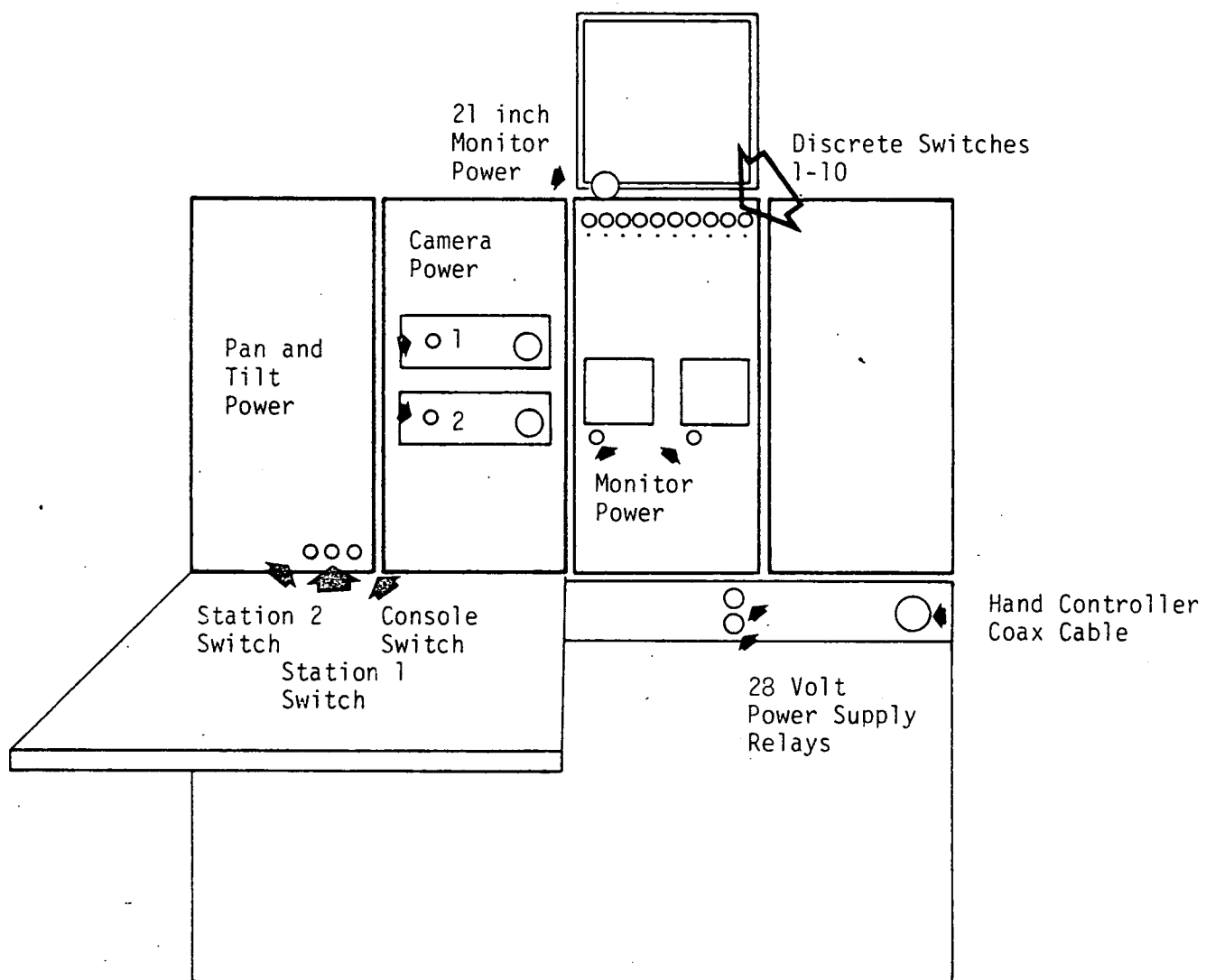


Figure 1 - Main Console in PFMA Controller Room

RM A127

STEP 3. In the ORBITAL SERVICER ROOM, visually inspect the position of the arm to make sure that it resides in the nominal rest position. Inspect the power supply panel to make sure elbow camera and main panel power are on and that the 15 Vdc and 28 Vdc toggles are on (up). Figure 2 illustrates the nominal states for both the arm and the panel. The joint switches 1, 2, 4, 5, 6, 7, 8 should be off (down).

RM 234

STEP 4. In the CONTROL ROOM:

1. Turn on Console Power Switch.
- 2a. Turn on Discrete Switch 1 for MSI 544 hand controller,
OR
- 2b. Turn on Discrete Switches 1 and 2 for MSI 404 hand controller.
3. Turn on Discrete Switch 8. At this point the computer should print several lines.
4. Turn on STAND 1 Switch, Pan and Tilt Power 1 and 2, Camera Switch 1 and 2, and Monitor Switches 1, 2, and 3.
When cameras and monitors warm up, PFMA Room and/or task board should be visible.
5. Turn Switch 8 off. This initiates the arm.
6. Turn Switch 5 on. This initializes "Hawk Mode" for training and testing.
7. Press Red 28 Vdc power button.

RM A127

STEP 5. Turn on joint switches 1, 2, 4, 5, 6, 7 and 7 in Room A127.

At this point, the Arm will move when force is applied to hand controller.

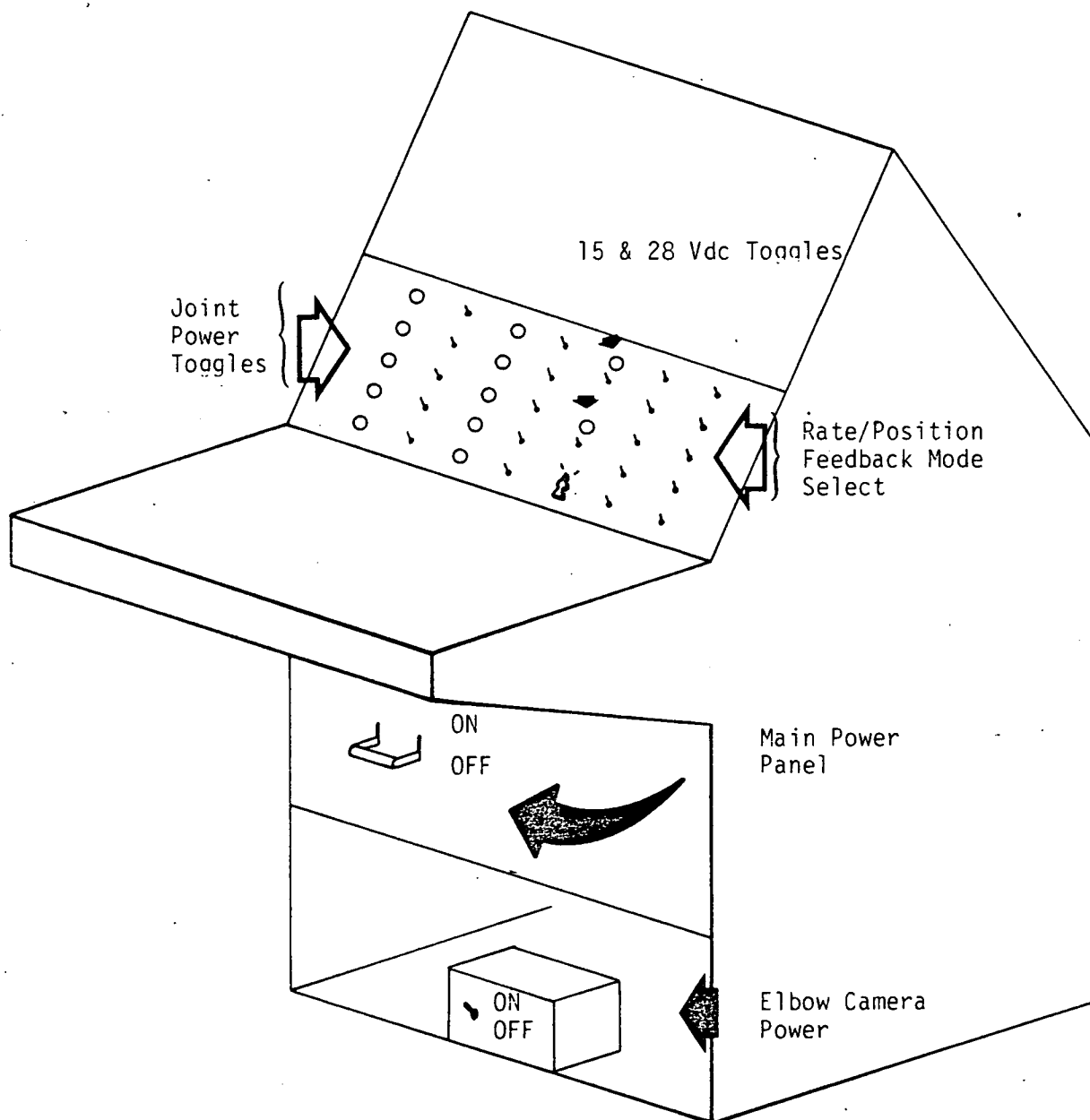
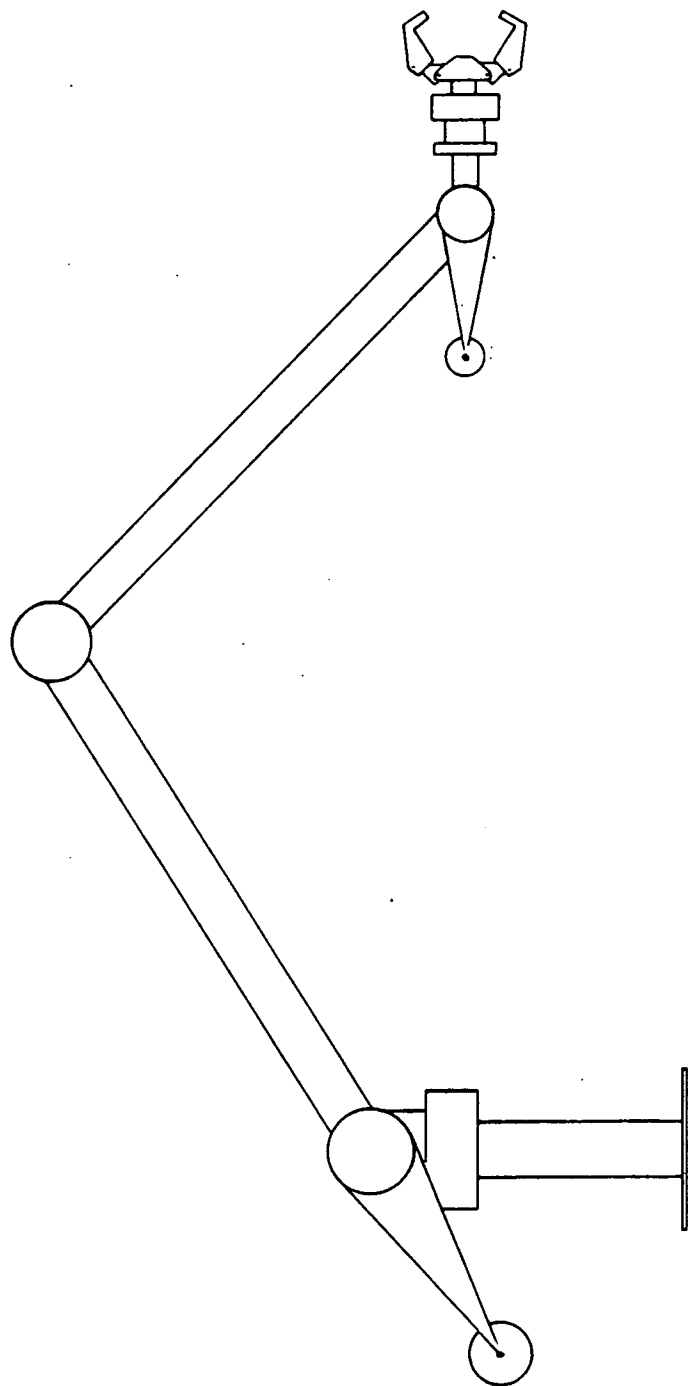


Figure 2 - Master Power and Power Toggles
for PFMA Joints in PFMA Room



Continuation, Figure 2 - Nominal Rest Position of the PFMA

CAUTIONARY NOTE:

If at any time the arm does not respond to control, i.e., continues moving with no inputs,

- A. Turn Switch 10 on. If arm still does not null out, turn Switch 10 off. Then turn Switch 8 on and off rapidly.
- B. Run quickly to Computer room and press Master Clear Switch on Printer.
- C. If arm still does not null out, then press black 28 Vdc OFF button on lower righthand console.

IF: Card reader stops prior to expelling last card, and the printer does not print anything, and the CRT/KB does not change last entry, then press "MASTER CLEAR" on printer and

OR: CRT/KB = HANG
 _001 (or 004)
then restart card reader,
then type in = "C" RETURN, Then card reader should continue to read deck.

IF: CRT/KB $\neq$ DONE, but
 = SEQN (or CKSM)
then there is an error in the card inputs.

Step 1: Turn key switch to Left

Step 2: On bottom row - HALT Press Down
 (left) CLEAR Simultaneously

Step 3: Bottom row - PAPERTAPE - Button Up
 (far right) LOAD - Press Down

Step 4: When paper tape read, then - HALT Press Down
 CLEAR Simultaneously

Step 5: Flick Down Quickly the "START" Button

then, CRT/KB = ENABLE PROGRAM PROTECT

CHANE

then, TURN KEY SWITCH TO RIGHT

then, GO TO STEP 2-D.

PROTOFLIGHT MANIPULATOR PROCEDURES - POWER DOWN

RM 234

STEP 1. In the PFMA CONTROL ROOM, do the following to power down (See Figure 1 for locations):

- A. Move arm to stowed position.
- B. Turn Switch 10 ON
- C. Turn Switch 9 ON
- D. Turn Switch 8 ON, then OFF several times (until printer does not print when 8 is turned on)
- E. Observe that arm is no longer in motion.

RM 236

STEP 2. In the SEL COMPUTER ROOM, check to see that the computer power is still ON. POWER OFF is the responsibility of SEL personnel and Essex will NOT bring the computer down.

- A. Turn key switch to Left
- B. On bottom row - HALT Press Down
(left) CLEAR Simultaneously
- C. Bottom row - PAPERTAPE - Button up
(far right) LOAD - Press Down
- D. When paper tape read, then - HALT Press Down
CLEAR Simultaneously
- E. Flick Down Quickly the "START" Button
then, CRT/KB = ENABLE PROGRAM PROTECT
CHANE
then, TURN KEY SWITCH TO RIGHT
- F. Turn switches 11, 17, 19, 21 = ON
- G. Type In on CRT/KB "CP_WW" RETURN
EX RETURN
PC RETURN
- H. Turn Switch 12 = ON

RM 234

STEP 3. In the CONTROL ROOM:

1. Press Black 28 Vdc power button.
2. Turn Off STAND 1 Switch, Pan and Tilt Power 1 and 2, Camera Switch 1 and 2, and Monitor Switches 1, 2, and 3.
3. Turn Switches 1-10 = OFF
4. Turn off Console Power Switch.

RM A127

STEP 3. In the ORBITAL SERVICER ROOM, Visually inspect the position of the arm to make sure that it resides in the nominal rest position. Inspect the power supply panel to make sure elbow camera and main panel power are on and that the 15 Vdc and 28 Vdc toggles are on (up). Figure 2 illustrates the nominal states for both the arm and the panel. The joint switches 1, 2, 4, 5, 6, 7, 8 should be turned off (down).



Appendix C

Protoflight Manipulator Arm Software


```

C
C MAIN PROGRAM USED TO SELECT THE PROPER HAND CONTROLLER
COMMON/DUMMY/IDUMM(1200)
COMMON/CTRL/C(9),XMINUS(9),IH,CSAV(9),KP
COMMON/VALUE/SCL(9),SKL(9),SL(6),IF
COMMON/TEST/IBUG,IO

C
C      INITIALIZE XMINUS(I) AND C(I)
C      CALL RSL(1BUG,7)
C      DO 1 I=2,9
C      XMINUS(I)=0.0
C      CONTINUE

1
C
C      READ SENSE LINE 8 -- N=0 OFF  N=1 ON
C      CONTINUE
C      CALL RSL(N,8)

C
C      CONTINUE LOOPING UNTIL IT HAS BEEN ENABLED
C      IF(N.EQ.0)GO TO 4
C      CALL CTRL

C
C      OUTPUT THE VALUES FOR THE USER TO SEE
C      WRITE(2,6)IF
6      FORMAT('HAND CONTROLLER NO, SELECTED',I5)
C      DO 10 I=1,9
C      WRITE(2,8)I,C(I),I,SCL(I),I,SKL(I)
8      FORMAT(' C(',I3,')=',6X,E16,9,' SCL(',I3,')=',6X,E16,9,
C      ' SKL(',I3,')=',6X,E16,9)
C      C(I)=0.0
10     CONTINUE
C      WRITE(2,11)
11     FORMAT(1H0)

C
C      NOW READ SENSE LINE UNTIL IT IS DISABLED
14     CONTINUE
C      CALL RSL(N,8)
C      IF(N.EQ.1)GO TO 14

C
C      IT HAS BEEN DISABLED - SO GO MOVE THE ARM / UNLESS EXIT
C      CALL RSL(J,9)
C      IF(J.EQ.0)CALL MOVE1(IF)
C      CALL RSL(J,9)
C      IF(J.EQ.0)GO TO 4

C
C      THIS IS THE END
C      CALL EXIT
END

```

NO ERRORS

```

C
C SUBROUTINE CNTRL
C SUBROUTINE CNTRL
C
C THIS ROUTINE INITIALIZES SCL / SKL AND ASSURES RI HAND RULE
C AND PHYSICAL LAWS AND VOLTAGE LIMITATIONS ARE MET
COMMON/VALUE/SCL(9),SKL(9),SL(6),K
COMMON/TEST/IBUG,10
COMMON/CTRL/C(9),XMINUS(9),JH,CSAV(9),KP
C
C IF HAND CONTROLLER ALREADY SELECTED=DON T DO IT AGAIN
C IF(K,NE,U)GO TO 10
C
C READ THE FIRST 3 SENSE LINES TO SEE WHICH HAND CONTROLLER
C IS TO BE USED
C
5 CONTINUE
DO 8 J=1,2
CALL RSL(J,1)
K=K+J
CONTINUE
8
C
C NOW TEST FOR PROPER VALUE SET / ERROR IF K=0
C K=K+1
10 CONTINUE
IF(K,EW,1)WRITE(10,12)
12 FORMAT('! ERROR ENCOUNTERED IN CNTRL ROUTINE ')
C
C ELSE BRANCH TO THE PROPER SECTION
C GO TO(2,13,14,15),K
C
C MSI 544 HAND CONTROLLER SECTION
C CONTINUE
13 CALL MSI(SCL,544)
RETURN
C
C MSI 404 HAND CONTROLLER SECTION
C CONTINUE
14 CALL MSI(SKL,404)
RETURN
C
C MSI 502 HAND CONTROLLER SECTION
C CONTINUE
15 RETURN
C
C THIS IS THE END
C END

```

NO ERRORS

```

C
C SUBROUTINE MSI
C SUBROUTINE MSI(SALE,MDS)
C
C THIS ROUTINE IS USED WITH THE MSI HAND CONTROLLERS-544 AND 404
C COMMON/CTRL/C(9),XMINUS(9),IHAWK,CSAV(9),KP
C COMMON/TEST/IBUG,10
C DIMENSION SALE(9)
C
C SCALE ALL OF THE CONTROL VALUES-C(1)
C DO 5 I=2,9
C   CSAV(I)=C(I)
C   CALL RIES(I+22,1,C(I),SALE(I))
C   CONTINUE
5
C
C SET ARRAY AND CALIBRATE THE C'S
C IF(1BUG.EQ.1)WRITE(10,7)(I,C(I),I=1,9)
C 7 FORMAT(3(' C(',11,') = ',E16,9)/)
C CALL SEAIT(MDS)
C
C CHECK STATUS OF SWITCHES A AND B AND TRIGGER
C IF(ABS(C(8)),LT,0.0400)GO TO 8
C
C TRIGGER PULLED
C C(8)=1.0
C GO TO 9
C
C TRIGGER NOT PULLED
C CONTINUE
C C(8)=0.0
C
C CHECK FOR NEITHER SWITCH
C CONTINUE
C IF(ABS(C(9)),LT,0.1100)GO TO 19
C
C SWITCH A
C IF(C(9).GT,0.0)GO TO 10
C C(9)=-9.999999999
C GO TO 20
C
C SWITCH B
C CONTINUE
C C(9)=9.999999999
C GO TO 20
C
C NEITHER
C CONTINUE
C C(9)=0.0
C
C END IT ALL
C CONTINUE
C TEMP=C(5)
C C(5)=C(9)
C C(9)=C(TEMP)+CSAV(9)
C
C THIS IS THE PLACE TO RETURN FROM
C RETURN
C END

```

```

C
C SUBROUTINE MOVEIT
C SUBROUTINE MOVEIT(IHAND)
C
C THIS ROUTINE WILL DO WHAT IS NECESSARY TO MOVE THE PFMA ON A
C JOINT-BY-JOINT BASIS
C COMMON/BACKSL/AXIS(4,8),SCAL
C COMMON/TEST/IBUG,10
C COMMON/FA/FACU(8)
C COMMON/CIRL/C(9),XMINUS(9),IHAWK,USAV(9),KP
C
C ZERO D/A CHANNELS
C DO 5 I=14,21
C CALL WDACS(I-1,1,0,0,1,0)
5 CONTINUE
C
C SELECT SWITCH 10 FOR EMERGENCY STOP
C CONTINUE
C CALL RSL(1,10)
C IF(1,EQ,1)GO TO 65
C
C GET SCALE FACTOR
C DO 11 J=1,2
C IS=J
C CALL RSL(K,J)
C
C SCALE FACTOR SELECTED
C IF(K,EQ,1)GO TO 13
C
C NO! YET
C CONTINUE
C IS=0
C
C SCALE FACTOR IS 2**IS
C CONTINUE
C SCALE=(2,0**IS)*10.0
C
C INPUT COMMANDS HERE TO MOVE THE PFMA
C CALL CNTRL
C
C IF MSI 404 SELECTED SETUP FOR DEADBAND
C IF(IHAND,EQ,3)CALL DEADB
C
C HOW ABOUT THE SHOULDER+ELBOW OR JUST ELBOW
C IF(ABS(C(6)),LT,(AXIS(3,7)*SCAL))C(6)=0.0
C
C YOU MUST REALLY WANT TO MOVE IT
C C6=C(6)/SCAL
C
C DO WE CHANGE THE MULT FACTOR
C IF(IHAWK,EQ,1)CALL RSL(1,FAU,7)
C IF(1,FAU,EQ,1)CALL FACT(1)
C
C BACK TO THE MAIN STREAM
C IF((C(8),LT,0.90),AND,(IHAWK,EQ,1))C6=C6*FACU(1)
C IF((IBUG,FQ,1),AND,(C6,NE,0.0))WRITE(10,23)C6,SCAL
23 FORMAT(1 ELBOW PITCH GIVEN ',F7.3,' VOLTS ', SCAL =',
C F8.3)

```

```

C
C      DO THE PHIL TRANSFORMATION
C      CALL RSL(KP,4)
C
C      NOW MOVE THE JOINT
C      IF((C(8),LT,0,90),AND,(KP,EQ,0))CALL WDAGR(16,C6)
C      IF((C(8),LT,0,90),AND,(KP,EQ,1))CALL WDAGR(16,-C6)
C      IF((C(8),GT,0,90)CALL WDAGR(16,-C6)
C      IF((C(8),LT,0,90),AND,(IHAWK,EQ,1))C6=C6/FACQ(1)
C      CALL WHERE(4)
C
C      DO WE CHANGE THE MULT FACTOR
C      IF(IHAWK,EQ,1)CALL RSL(IFAQ,7)
C      IF(IFAQ,EQ,1)CALL FACT(2)
C
C      BACK TO THE MAIN STREAM
C      IF((C(8),GT,0,90),AND,(IHAWK,EQ,1))C6=C6*FACQ(2)
C      IF((C(8),LT,0,90),AND,(IHAWK,NE,1))C6=0.0
C
C      NOW OUTPUT SHOULDER
C      IF((IBUG,EQ,1),AND,(C6,NE,0,0))WRITE(10,32)C6,SCAL
32  FORMAT(' SHOULDER PITCH GIVEN ',F7,3,' VOLTS ', ' SCAL
      'L = ',F8,3)
C      CALL WDAGR(14,C6)
C      IF((C(8),GT,0,90),AND,(IHAWK,EQ,1))C6=C6/FACQ(2)
C      CALL WHERE(2)
C
C      NOW ABOUT SHOULDER YAW
C      IF(ABS(C(7)),LT,AXIS(3,5)*SCAL)C(7)=0.0
C
C      YOU MUST REALLY WANT TO MOVE IT
C      C7=C(7)/SCAL
C      IF((IBUG,EQ,1),AND,(C7,NE,0,0))WRITE(10,37)C7,SCAL
37  FORMAT(' SHOULDER YAW GIVEN ',F7,3,' VOLTS ', ' SCAL = '
      'L = ',F8,3)
C      CALL WDAGR(13,C7)
C      CALL WHERE(1)
C
C      NOW ABOUT WRIST PITCH
C      IF(ABS(C(4)),LT,AXIS(3,3)*SCAL)C(4)=0.0
C
C      YOU MUST REALLY WANT TO MOVE IT
C      C4=C(4)/SCAL
C      IF((IBUG,EQ,1),AND,(C4,NE,0,0))WRITE(10,43)C4,SCAL
43  FORMAT(' WRIST PITCH GIVEN ',F7,3,' VOLTS ', ' SCAL = '
      'F0,3)
C      CALL WDAGR(17,C4)
C      CALL WHERE(5)
C
C      NOW ABOUT WRIST YAW
C      IF(ABS(C(3)),LT,AXIS(3,2))C(3)=0.0
C
C      YOU MUST REALLY WANT TO MOVE IT
C      C3=C(3)/SCAL
C      IF((IBUG,EQ,1),AND,(C3,NE,0,0))WRITE(10,47)C3,SCAL
47  FORMAT(' WRIST YAW GIVEN ',F7,3,' VOLTS ', ' SCAL = ',
      'F0,3)
C      CALL WDAGR(18,C3)
C      CALL WHERE(6)

```

```

C
C      NOW ABOUT WRIST ROLL
C      IF (ABS(C(9)),LT,AXIS(3,1))C(9)=0,0
C
C      YOU MUST REALLY WANT TO MOVE IT
C      C9=C(9)/SCAL
C      IF ((IBUG,EQ,1),AND,(C9,NE,0,0))WRITE(10,53)C9,SCAL
53      FORMAT(, WRIST ROLL GIVEN 1,F7,3,' VOLTS ', ' SCAL = '
C      F8,3)
C      CALL WDCR(19,C9)
C      CALL WHERE(7)
C
C      NOW ABOUT THE JAWS
C      IF (ABS(C(5)),LT,0,90)C(5)=0,0
C
C      YOU MUST REALLY WANT TO MOVE IT
C      C5=C(5)/10,0
C      IF ((IBUG,EQ,1),AND,(C5,NE,0,0))WRITE(10,57)C5
57      FORMAT(, JAWS GIVEN 1,F7,3,' VOLTS ')
C      CALL WDCR(20,C5)
C
C      NOW IF HAWK MODE SELECTED DRIVE IT
C      CALL RSL(IHAWK,5)
C      IF (IHAWK,EQ,1)CALL HAWK
C
C      EVERYONE HAS HAD A CHANCE TO MOVE=GIVE THEM ANOTHER ONE
C      GO TO 8
C
C      NOW IS THE TIME FOR ALL GOOD PFMA S TO STOP
62      CONTINUE
C      DO 70 I=14,21
C      CALL WDAUS(I-1,1,0,0,1,0)
70      CONTINUE
C
C      THIS IS ALL RETURN
C      RETURN
C
C      THIS IS THE END
C      END

```

NO ERRORS


```

C
C SUBROUTINE HAWK
C SUBROUTINE HAWK
C
C THIS SUBROUTINE DOES THE DRIVING FOR THE HAWK MODE
COMMON/CTRL/C(9),XMINUS(9),IH,CSAV(9),KP
COMMON/TEST/IBUG,10
COMMON/FA/FACU(8)
COMMON/BKKRLS/AXIS(4,8),SCAL
COMMON/L0C/THETA(7),ZERO(7),RATE(7),TIME(7)
TAN(X)=SIN(X)/COS(X)
C
C CALCULATE THE RATES NECESSARY
THETA1=THETA(2)*THETA(4)+THETA(5)
RATE(7)=(RATE(1)*SIN(THETA1))/COS(THETA(6))
RATE(6)=-RATE(1)*COS(THETA1)
RATE(5)=-THETA(4)-THETA(2)*RATE(1)*SIN(THETA1)*TAN(THETA(6))
C
C NOW CALCULATE THE DRIVES
C(4)=(RATE(7)/ZERO(5))*1.E-3
C(3)=RATE(6)/ZERO(6)
C(9)=RATE(7)/ZERO(7)
C
C NOW DO THE WRIST PITCH
IF(C(8).LT,0.90)C(4)=6.00*C(4)
C
C DO WE CHANGE THE MULT FACTOR
CALL RSL(IFAQ,7)
IF(IFAQ,EQ,1)CALL FACT(3)
C
C BACK TO THE MAIN STREAM
IF((C(8).LT,0.90).AND,(KP,EQ,1))C(4)=FACU(5)*C(4)
IF(ABS(C(4)).LT,AXIS(3,3)*SCAL)GO TO 10
CALL CALIB(C(4),XMINUS(4),0.999999999)
C(4)=C(4)/SCAL
IF(1BUG,EQ,1)WRITE(10,8)C(4)
8 FORMAT(' WRIST PITCH GIVEN ',F7,3,' VOLTS=HAWK MODE')
CALL WDAGR(17,C(4))
C(4)=C(4)*SCAL
C
C NOW DO THE WRIST YAW
10 CONTINUE
IF(ABS(C(3)).LT,AXIS(3,2))GO TO 20
CALL CALIB(C(3),XMINUS(3),0.999999999)
IF(1BUG,EQ,1)WRITE(10,18)C(3)
18 FORMAT(' WRIST YAW GIVEN ',F7,3,' VOLTS=HAWK MODE')
CALL WDAGR(18,C(3))
C(3)=C(3)*SCAL
C
C NOW DO THE WRIST ROLL
20 CONTINUE
IF(ABS(C(9)).LT,AXIS(1,1))GO TO 30
CALL CALIB(C(9),XMINUS(9),0.999999999)
IF(1BUG,EQ,1)WRITE(10,28)C(9)
28 FORMAT(' WRIST ROLL GIVEN ',F7,3,' VOLTS=HAWK MODE')
CALL WDAGR(19,C(9))
C(9)=C(9)*SCAL
C

```

```
C      NOW GET THE NEXT INPUT
30     CONTINUE
      RETURN

C
C     END HERE
      END

NO ERRORS
```

```

C
C      SUBROUTINE WHERE
C      SUBROUTINE WHERE(JOINT)
C
C      THIS SUBROUTINE FIGURES OUT WHERE THE ARM IS
C      COMMON/L00/THETA(?),ZERO(?),RATE(?),TIME(?)
C
C      READ THE FEEDBACK OUTPUTS
C      CALL RCLK(1XYZ1)
C      CALL RTES(JOINT,1,1,RATE(JOINT),ZERO(JOINT))
C      CALL RCLK(1XYZ2)
C      XYZ1=FLOAT(1XYZ1)
C      XYZ2=FLOAT(1XYZ2)
C      TIME(JOINT)=ABS(XYZ2-XYZ1)
C      THETA(JOINT)=RATE(JOINT)*TIME(JOINT)
C
C      RETURN FROM HERE
C      RETURN
C
C      END !! ALL
C      END

```

NO ERRORS

```

C
C SUBROUTINE FACT
C SUBROUTINE FACT(I)
C
C THIS ROUTINE USED TO MANUALLY CHANGE THE FACTORS IN THE HAWK MODE
COMMON/TEST/IBUG,10
COMMON/FA/FACQ(8)
C
C PICK THE ROUTINE
GO TO(10,20,30),I
C
C ELBOW
C
10 CONTINUE
WRITE(10,12)FACQ(I)
12 FORMAT(' THE ELBOW FACTOR IS ',F7,4)
READ(1,14)FP
14 FORMAT(F7,4)
C
C SAME OR CHANGE
IF(FP,EQ,0,0)GO TO 90
FACQ(I)=FP
GO TO 90
C
C SHOULDER
C
20 CONTINUE
WRITE(10,22)FACQ(I)
22 FORMAT(' THE SHOULDER FACTOR IS ',F7,4)
READ(1,14)FP
C
C SAME OR CHANGE
IF(FP,EQ,0,0)GO TO 90
FACQ(I)=FP
GO TO 90
C
C WRIST
C
30 CONTINUE
WRITE(10,32)FACQ(I)
32 FORMAT(' THE WRIST FACTOR IS ',F7,4)
READ(1,14)FP
C
C SAME OR CHANGE
IF(FP,EQ,0,0)GO TO 90
FACQ(I)=FP
C
C THIS IS IT
90 CONTINUE
RETURN
END

```

NO ERRORS

```

C
C SUBROUTINE SE111
C SUBROUTINE SE111(MDS)
C
C THIS SUBROUTINE SETS THE INITIAL VALUES IN ARRAY AND THEN CALIBRAT
C C(1) FOREVER
COMMON/CTRL/C(9),XMINUS(9),IH,CSAV(9),KP
COMMON/ARK/ARRAY(9)
COMMON/TEST/IBUG,10
C
C     SET ARRAY(JK)
C     CALL RSL(J,3)
C     DO 22 JK=2,9
C
C         HAS ARRAY(JK) ALREADY BEEN SET
C         IF((J.EQ.0).AND.(ARRAY(JK).NE.0,0))GO TO 11
C
C         NO-DO IT HERE
C         FP=1,0
C         IF(C(JK).LT.0,0)FP=-1,0
C         ARRAY(JK)=ABS(C(JK))
C         ARRAY(JK)=FP*ARRAY(JK)
C
C         YES-CONTINUE HERE
C         CONTINUE
C
C         IF NOT HAWK MODE-ZERO CSAV ARRAY
C         IF(IH.NE.1)CSAV(JK)=0,0
C         C(JK)=C(JK)+ARRAY(JK)
C
C         DO WE CALIBRATE NOW
C         CALL CALIB(C(JK),XMINUS(JK),9,999999999)
C
C     END LOOP
C     CONTINUE
C
C     IS IT THE 544 HAND CONTROLLER
C     IF((J.EQ.1).OR.(IBUG.EQ.1))WRITE(10,24)(1,C(I),I=1,9)
C     24 FORMAT(3(3(' C',11,') = ',E16,9)/))
C     IF(MDS.EQ.404)GO TO 25
C     C(3)=C(3)+CPAV(3)
C     C(4)=C(4)+CSAV(4)
C     GO TO 30
C
C     IT MUST BE THE 404 - CORRECT CONVENTION
C     CONTINUE
C     CTEMP=C(2)
C     C(2)=C(3)
C     C(3)=CTEMP
C     CTEMP=C(4)
C     C(4)=C(3)+CSAV(4)
C     C(3)=CTEMP+CSAV(3)
C
C     THIS IS AS GOOD A PLACE TO RETURN AS ANY-ALSO AUTOMATE IBUG
C     CONTINUE
C     CALL RSL(IBUG,7)
C
C     SET UP IO UNIT

```



```
      CALL RSL(IB,9)
      IO=5
      IF(IB,EQ,0)IO=2
C
C      NOW DO II
      RETURN
C
C      END II ALL
      END
NO ERRORS
```



```

C
C  SUBROUTINE CALIB
C  SUBROUTINE CALIB(C,XMINUS,X)
C
C  THIS SUBROUTINE WILL CALIBRATE THE C(I) S
C  FP=1.0
C
C      WELL=IS THERE AN XMINUS TO USE
C      XMINUS=ABS(C)-X
C      IF(XMINUS,LT.0.0)XMINUS=0.0
C
C      DO WE ADD OR SUBTRACT
C      IF(C,LT.0.0)FP=-1.0
C      C=ABS(C)-XMINUS
C      C=FP*C
C
C  RETURN
C  RETURN
C
C  END !! ALL
C  END

```

NO ERRORS

```

C
C      SUBROUTINE DEADB
C      SUBROUTINE DEADB
C
C      THIS ROUTINE WILL SET THE DEADBAND VALUES FOR THE MSI 404 HAND
C      CONTROLLER
C      COMMON/DEAD/DB(9)
C      COMMON/CTRL/C(9),XMINUS(9),IH,CSAV(9),KP
C
C      SEE IF ANY OF THE JOINTS HAVE EXCEEDED THE DEADBAND LIMITS
C      DO 10 I=2,7
C      CSAVE=C(I)
C      CALL CALIB(C(I),XMINUS(I),DB(I))
C
C      WAS IT GREATER THAN THE DEADBAND
C      IF(XMINUS(I),NE,0.0)GO TO 5
C
C      NO IT WASN'T - SO ZERO IT
C      C(I)=0.0
C      GO TO 10
C
C      WELL IT IS GREATER THAN DEADBAND
C      CONTINUE
C      FP=1.0
C      IF(C(I),LT,0.0)FP=-1.0
C      C(I)=ABS(CSAVE)*DB(I)
C      C(I)=FP*C(I)
C
C      CONTINUE HERE
C      CONTINUE
C
C      IF ALL OVER
C      RETURN
C
C      END IF ALL
C      END

```

NO ERRORS

BLOCK DATA
BLOCK DATA

THIS ROUTINE INITIALIZES ALL OF THE DATA NEEDED BY OTHER ROUTINES
COMMON/CTRL/C(9),XMI,US(9),IH,CSAV(9),KP
COMMON/VALUE/SCL(9),SKL(9),SL(6),K
COMMON/WRKRLS/AXIS(4,8),SCAL
COMMON/ARR/ARRAY(9)
COMMON/DEAD/DB(9)
COMMON/TEST/IBUG,10
COMMON/PA/FACW(8)
COMMON/LBC/THETA(7),ZERO(7),RATE(7),TIME(7)

INITIALIZE THE DATA VALUES

DATA C(1),C(2),C(3),C(4),C(5),C(6),C(7),C(8),C(9)/9*0.0/

DATA SCL(1),SCL(2),SCL(3),SCL(4),SCL(5),SCL(6),SCL(7),SCL(8),
SCL(9)/2*1.0,-75,85182194,87,24174667,-16,7782898
-16,22392396,-16,45648081,2*1.0/

DATA SKL(1),SKL(2),SKL(3),SKL(4),SKL(5),SKL(6),SKL(7),SKL(8),
SKL(9)/0,0,10,0,85,62453791,-84,00820404,0,0,-10,0,
10,0,0244201,2*1.0/

DATA SL(1),SL(2),SL(3),SL(4),SL(5),SL(6)/
5,0, 2,5, 5,0, 5,0, 3,33, 5,0/

WRIST ROLL

DATA AXIS(1,1),AXIS(2,1),AXIS(3,1),AXIS(4,1)/,17,-,15,,12,-,09/

WRIST YAW

DATA AXIS(1,2),AXIS(2,2),AXIS(3,2),AXIS(4,2)/,16,-,16,,08,-,10/

WRIST PITCH

DATA AXIS(1,3),AXIS(2,3),AXIS(3,3),AXIS(4,3)/,10,-,07,,07,-,04/

SHOULDER PITCH

DATA AXIS(1,4),AXIS(2,4),AXIS(3,4),AXIS(4,4)/,05,-,04,,04,-,03/

SHOULDER YAW

DATA AXIS(1,5),AXIS(2,5),AXIS(3,5),AXIS(4,5)/,05,-,04,,04,-,03/

SHOULDER ROLL

DATA AXIS(1,6),AXIS(2,6),AXIS(3,6),AXIS(4,6)/4*0.0/

ELBOW

DATA AXIS(1,7),AXIS(2,7),AXIS(3,7),AXIS(4,7)/,05,-,04,,04,-,03/

JAW

DATA AXIS(1,8),AXIS(2,8),AXIS(3,8),AXIS(4,8)/,04,-,04,,03,-,03/

DEAD BANDS FOR MSI 404

DATA DB(1),DB(2),DB(3),DB(4),DB(5),DB(6),DB(7),DB(8),DB(9)
/20,0, 0.99, 0.50, 0.50, 0.99, 0.99, 0.99, 0.00, 0.00 /

MISCELLANEOUS

DATA K/0/

DATA 1H/0/

DATA 1BUG/0/,10/5/

C

C

ARRAY 10 RETURN ALL AXISES 10 ZERO

DATA 1A ARRAY(1),ARRAY(2),ARRAY(3),ARRAY(4),ARRAY(5),ARRAY(6),

ARRAY(7),ARRAY(8),ARRAY(9)/9*0,0/

C

C

RATE CALIBRATION VALUE

DATA 1A ZERO(1)/0,5E=6/

.. ZERO(2)/0,5E=6/

.. ZERO(3)/0,5E=6/

.. ZERO(4)/0,5E=6/

.. ZERO(5)/0,5E=6/

.. ZERO(6)/0,5E=6/

.. ZERO(7)/0,5E=6/

C

C

FACORS

DATA 1A FACQ(1),FACQ(2),FACQ(3),FACQ(4),FACQ(5),FACQ(6),FACQ(7),

.. FACQ(8)/0,30,0,25,0,30,5*1,0/

C

C

THIS IS THE END

END

NO ERRORS

LANGLEY RESEARCH CENTER



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